RETURN *ON* CARBON

A METHOD FOR THE ASSESSMENT OF ECONOMIC RETURN PER CARBON EMITTED APPLIED TO DESIGN ALTERNATIVES FOR A RESIDENTIAL RENTAL DEVELOPMENT IN BERLIN-TREPTOW

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Abstract

This study develops the term ‘Return on Carbon’, a novel measure of efficiency for real-estate projects, defined as the quotient of financial yield per carbon emitted annually.

For the study of this measure, a site in Berlin-Treptow is proposed. The site is well-suited for the development of a small multifamily rental property in the form of a row house with a total built area potential of 337 m^2.

In order to generate insight into the resulting Return on Carbon of a design, multiple alternatives are developed for the site according to a framework, consisting of a combination of building typology, constructive concept and energy system. Based on this framework, a total of 32 permutations are developed. For each aspect of the design alternatives a base case is defined which represents common local construction practice.

The typologies considered include the main residential rental models appropriate for the site, namely either 6 Mini-Apartments, 3 Flats, 2 Multilevel Units, or a single undivided Coop-House. Two constructive concepts are examined, which respectively make use of Masonry and Wood as a base material. Several energy systems are analysed, offering a range of solutions both with and without fossil fuels as a source of energy and the potential of meeting the building demands with low carbon emissions.

Sample calculations are provided for the assessment of the design alternatives according to the Return on Carbon methodology. A goal of the method is to examine the initial as well as the operational stage of the building lifecycle. Economically, the method considers the project’s initial investment, as well as ongoing operating costs and revenues. Equally, in terms of carbon emissions, both the initial investment (embodied emissions), as well as the ongoing impacts are taken into consideration.

For modeling and simulation, various domain specific software tools are applied. Namely, McNeel’s Rhino is used for spatial planning, Design Builder and U-wert.net are applied to simulate and evaluate the physical properties of the building envelope, while PolySun is used to simulate the building systems, and GREG to tabulate the embodied emissions of the building.

Market data, data from the German Construction Cost Index (BKI) as well as the KBOB Life Cycle Assessment Database are assembled and incorporated into the assessment.

Finally, the resulting Return on Carbon for the 32 design alternatives is presented and the influence of the building typology, construction concept and energy system are discussed.

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Thank you to Axel Paulus and Hannes Reichel for initially supporting my interest in building process and helping me to lay the foundation for the master thesis in an earlier study. Thank you to Estefania Tapias Pedraza and Amr Elesawy who offered me direction in the early days defining my master thesis. Thank you as well to Lauren Lallemand, Justine Dorion and K.L. Barth for their kind review of the work.

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Foreword

When I arrived in Berlin in 2012, I became instantly fascinated with the architecture and building typologies of the city. Previously trained as a mechanical engineer and with experience in the energy industry, I brought this background to Berlin where I worked on a technology project in the real-estate industry for two years.

The desire to develop architectural projects of my own had taken hold by the time I was accepted into the unique ETH Zurich master course of Building Systems in 2014. From the world-renowned departments of Architecture and Engineering of ETH Zurich, this program offered me a great deal of scientific and practical knowledge about construction, in a manner respectful both to society and environment.

Through the program in April 2016, Wilko Potgeter and I completed a study of economic models for the development of residential projects in the ‘transformational areas’ of Berlin, entitled ‘Investieren in Berlin’. In November of the same year, I put the study into practice when I made the first attempt to acquire a parcel of land in Berlin-Treptow, through a blind auction process organised by a Germany federal agency (Bundesanstalt für Immobilienaufgaben). In order to establish my offer price and to support the development of a business case, I applied the techniques described in our study.

I later came to learn that my offer was conservative, less than half of the winning bid. This was not due to a fundamental error in the model, in fact it would have supported making a higher offer, rather it had to do with not yet having calibrated the model (and myself) in practice, and therefore not having the confidence to risk more financially. Nonetheless, this exercise re-confirmed the usefulness of the work, and made clear to me how I should develop it further.

I had always intended that my Master Thesis would serve a practical end. Through the initial research and bidding process, I gained a connection with the small site in Berlin-Treptow, for which I was motivated to explore fully (as if the project had been my own) in answering the question: how can this site be used to its full potential? On the one hand, from the perspective of the developer – financially viable – and, on the other hand, from the perspective of the master of building systems – intelligent, and environmentally considerate.
In the end, the process of defining such an undertaking took close to one year.

For the project it was also important to me that questions of both engineering and architectural nature would be addressed, as I understood the overall intention of the master course to be. As a result, my thesis contains a design project for the site, generating numerous design alternatives, including selection of material and systems, as well as an analytical assessment of their performance in terms of a new expression of efficiency: Return on Carbon.

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Abbreviations

2000WS: 2000 Watt Society
AC: Alternating Current
ACH: Air Changes per Hour
ASHP: Air Source Heat Pump
AWF: Aussenwandsfläche (External Wall Area)
BGF: Brutto Geschossfläche (Total Built Area)
BKI: Baukosten Index (Building Cost Index)
COP: Coefficient of Performance
DAF: Dachfläche (Roof Area)
DEC: Domestic Electricity Consumption
DEF: Deckenfläche (Ceiling Area)
DHW: Domestic Hot Water
EBF: Energiebezugsfläche (Area with in Heated Envelope)
EE: End Energy
EnEV: Energieeinsparverordnung (Energy Conservation Act)
GRF: Gründungsfläche (Foundation Area)
GFZ: Geschossflächenzahl (Built Area Factor)
GSHP: Ground Source Heat Pump
Ht-Ex.: Heat Exchanger
IWF: Innenwandfläche (Interior Wall Area)
KfW: Kreditanstalt für Wiederaufbau
KG: Kostengruppe (Cost Group)
LCA: Life Cycle Assessment
LoD: Level of Detail
NUF: Nutzfläche (Usable Area)
MB: Merkblatt (Guideline)
PE: Primary Energy
PEF: Primary Energy Factor
PV: Photovoltaic
SH: Space Heating
SIA: Swiss Chamber of Engineers and Architects
STC: Solar Thermal Collection
TIPC: Total Initial Project Costs
U-Value: Overall Heat Transfer Coefficient
WDVS: Wärmedämmverbundsystem (Composite Thermal Insulation)
WRG: Wärmerückgewinnung (Heat Recovery)
WWR: Window to Wall Ratio
λ: Thermal Conductivity

Introduction

What does the Study do?

1. Describes the methodology of Return on Carbon
2. Proposes a site for a case study
3. Sets a structure for defining design alternatives for the site
4. Generates and refines 32 design alternatives
5. Assesses the Return on Carbon of the design alternatives

Real-Estate Trends

Real-estate is an exciting domain where constructions are brought into existence, ultimately having a massive impact on the community around them, physical and otherwise, for many subsequent years.

With significant portions of the world population living in or migrating to urban areas, the demand for residential space in cities is strong. Due to this phenomenon, the Pestel-Institute projects that Germany will require 400,000 new living units every year from 2015 until 2020 [1].

This challenge is compounded by the drive to simultaneously increase the energy efficiency of the building stock. European level efficiency targets are translated into the German EnEV regulation requiring the increased efficiency of any new constructions. By 2021, this regulation will require that all new buildings be of the lowest energy demand level (Niedrigstenenergiegebäude), effectively making them passive constructions [2].

The Role of Developer

For better or worse, the real-estate industry is not only a social enterprise with the goal of increasing the welfare of community members. It is also a business where market players profit through the creation, management and transaction of built objects. One of the most influential players in this industry is the developer, as they in some circumstances hold the power to decide what gets built; as they are the ones responsible for securing the financing of a project.

The inherent risk of this role is that if a developer sees a project primarily through an economic lens, they may disregard other important considerations, such as the impact of the project on the environment. It follows that developers may view EnEV and other efficiency regulations as a financial burden or limitation rather than an opportunity, especially given that improved building operational efficiency does not directly translate into increased revenue for the developer, or so it is perceived.

A goal of the thesis is to arrive at findings relevant to a developer, and thereby having the potential to influence their thinking and ultimately their impact on the built environment. In order to do so, the method developed incorporates environmental impacts, in the form of carbon emissions, into a familiar economic term, Return on Investment (ROI), in an effort to understand the carbon cost of turning a profit.

Return on Carbon, a novel Expression

Return on Carbon builds on the well know financial measure Return on Investment (ROI), where:

$$ROI = \frac{Net\ Revenue}{Total\ Investment\ (Developer)} \qquad [-]$$

From this foundation, Return on Carbon (ROC) is initially defined, as a real-estate industry specific term:

$$ROC = \frac{ROI}{Total\ Annual\ Emission\ per\ Area} \qquad [\mathrm{m}^2/\mathrm{kg}]$$

Through the development of the study, the benefit of a generalized term (i.e. none real-estate specific) is identified, and is defined as Modified ROC:

$$Modified\ ROC = \frac{Net\ Revenue}{Total\ Annual\ Emissions} \qquad [€/\mathrm{kg}]$$

Efficiency Standards and Methods

This study references and builds on numerous existing methods.

In order to check compliance with the EnEV regulation, a method is followed in which performance of the building envelope, performance of the energy system, as well as the fuel source(s) are taken into consideration [3], so as to ensure that the resulting annual energy demand is less than a limiting value. This is helpful to understand operational performance, however, embodied energy and emissions of the construction materials and systems which have gone into the building are neglected.

Embodied emissions are the equivalent mass of CO2 emitted for the creation of a material or product, and as the operational performance of buildings increase, the embodied emissions will come to represent a greater proportion of impacts.

Moreover, if one is interested in thoroughly understanding the efficiency of a building, it is necessary to consider both the initial emissions as well as the operational emissions. This is analogous to the understanding of the financial performance of a project as a function of both initial construction cost as well as ongoing costs. Therefore, while one can apply EnEV to assess operational performance, it cannot be depended on exclusively to assess overall building efficiency.

Based on the EnEV methodology, there exists currently a more stringent energy efficiency goal in Germany referred to as KfW 40, which is effectively 40% of the original EnEV limiting value [4]. Although KfW 40 also does not consider embodied emissions, this goal can be considered.

Within the same line of thinking exists the Passivhaus standard [5]. This standard sets a limit of 15 kWh/m^2 as the maximum annual energy which can be expended in treating a building's heated area.

A different type of method altogether, is the philosophy developed by the 2000 Watt Society (2000WS) which applies to building efficiency. The fundamental concept of this society is that a person is allocated 2000 W of continuous power, from which everything they need to live and consume is produced, and with which all embodied energy investments are covered [6]. The society also states a limit for CO2 emissions which can be broken down into allotments for building construction, and for building operation, among others. In this way it can be said that the 2000WS has a holistic approach which considers both embodied and operational energy and emissions.

Despite the fact that Western societies are currently far above the goals proposed by the 2000WS, their thinking was brought into the mainstream Swiss construction industry by the Swiss Chamber of Engineers and Architects (SIA) when they published guidelines MB 2040 [7], which proposes routes to achieve certain 2000WS goals by year 2050, as well as the publication MB 2032 [8], which recommends the calculation of embodied energy for building and puts forward an accounting method.

As part of describing routes to the 2000WS goals, MB 2040 provides reference values for carbon emissions on a per meter basis per year for the construction (8.5 kg/m^2) and operation (2.5 m^2) of a building. The guideline also provides values for mobility; however, this is outside the scope of the current study and therefore not considered. The MB 2032 accounting methodology refers to a database provided by the KBOB which includes impacts for all kinds of construction materials both in terms of embodied energy as well as emissions.

Given that these well-defined tools have no equivalent in the German market, they are applied in the current study to assess embodied impacts.

Financial Methods and Considerations

There is no shortage of methods to choose from when assessing the economic performance of a project. The measure of ROI (referred to as 'Rendite' in German) is applied in the study as it is thorough and has no obvious shortcoming from an economic perspective.

ROI requires assessing Net Revenues, therefore all incomes and costs including contributions towards future expenses, as well as the initial investment [9]. ROI is calculated as an annual snapshot, based on the assumption that the project will continue to exist as a rental object into the future. Therefore, no project lifetime needs to be defined, which is helpful, as it is difficult to predict when and how a major change to the project may occur in the future.

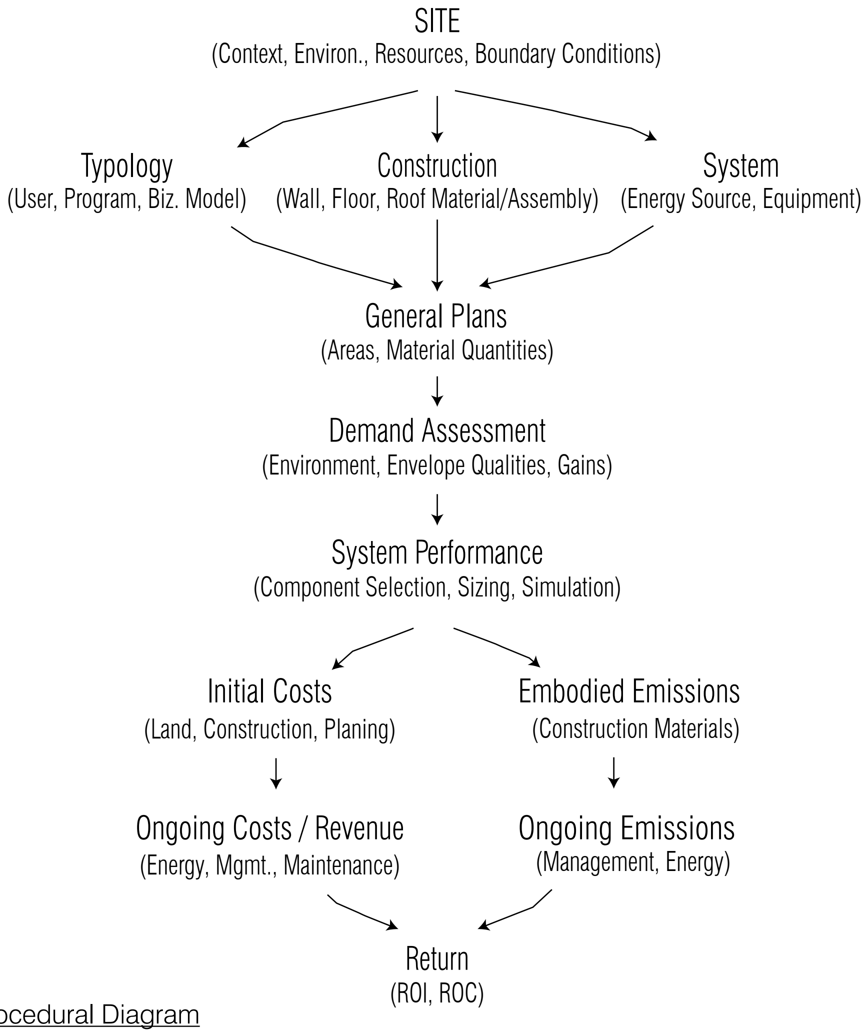
Industry data is called on to feed the model. The German Chamber of Architects' published Construction Cost Index (BKI) provides the basis for statistical reference costing in the study, whereby values from existing constructions are used to assess comparable projects. Furthermore online rental platforms such as ImmoblienScout and ImmoNet supply market data on rental prices.

In the pre-study to the master thesis, ‘Investieren in Berlin’ [10], it was shown that the development of rental objects is preferable over sale objects for sites outside of the Berlin city core, as sale prices in these outside areas are simply not high enough to cover the costs of the project and provide an attractive margin for a developer, specifically for smaller projects. As this is the case for the site under evaluation, only a rental scenario is considered in the study.

For all scenarios, a fixed interest rate of 1.4% is considered available from the bank for a qualified developer. Additionally, a fixed proportion of capital to loan of 34% is applied. The market price for the land is taken as €225’000 from discussions with the acquirer [11] and is held constant for all scenarios.

Procedure

The procedure followed in the study includes the 12 points illustrated in the Procedural Diagram.



Procedural Diagram

Site Selection

1. Site Selection: Identify and define the boundary conditions of a site suitable for evaluation.

Design Alternatives

2. Typology Definition: define typologies appropriate to the site, their associated spatial requirements, user profiles and business model.
3. Construction Definition: define construction concepts including materials, components and their method of assembly elaborated with construction diagrams.
4. Systems Definition: to meet the demands of the building's users, define technical systems appropriate for the local environment (taking advantage of the site resources), while being suitable for the building form and layout.

Analysis Method

5. Plans: through the drawing of plans, sections and elevations, prove the feasibility of all typologies, and evaluate their areas and material requirements.
6. Demand Assessment: assess the energy balance of the building based on the qualities of its envelope, the local climate, and user activities with the help of a building model developed in Design Builder building physics software.
7. System Performance: model and simulate the performance of the technical systems in order to meet the building energy demand, with the Polysun software.
8. Initial Costs: apply industry standard reference values for Berlin, Germany, to assess the construction costs of the design alternatives.
9. Operating Revenue: determine the revenues based on rental price market data from large German online real-estate transaction platforms and the rentable areas of the typologies.
10. Operating Costs: assess the variety of operating cost relevant to both the developer and the renter (i.e. management, maintenance, interest, energy, etc.)
11. Embodied Emissions: assess the embodied energy of the design alternatives via a database of material impacts.
12. Operating Emissions: assess the costs and greenhouse gas emissions of operating the proposed design.

Generate Results

13. Returns: through the integration of the analysis method, generate the final results in terms of return (ROI and ROC) and discuss the influence of the typology, construction and system on these.

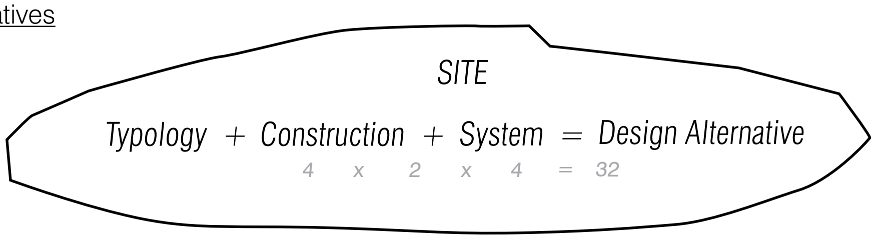
An Actual Site

Rather than evaluating plans of an existing project, an objective of the study is to develop design alternatives for a site of interest in the Behringstrasse of Berlin-Treptow, which at the time of this study was in its planning phase. The options developed are meant to be applicable in practice, therefore designs should be considerate of the local building norms so that they could possibly be implemented.

How can a Site be used to its full Potential?

In an attempt to answer the question of how the Behringstrasse site can be used to its full potential, numerous design alternatives are evaluated in terms of ROI and ROC. The generation of design alternatives is facilitated by a clear definition, whereby defined as the combination of a typology, construction and system. In total 32 design alternatives are generated as the permutations of 4 typologies, 2 constructions and 4 systems.
By evaluating a number of carefully selected and relevant design alternatives, it is asserted that there is a greater possibility of finding a practically optimal solution for the site.

Desing Alternatives



A further goal of the study is to gain insights into solution types offered by the specific choice and combination of typology, construction and system, which could then be applied to other projects.

Based on the analysis method, fully integrated results including ROI and ROC for all 32 design alternatives are charted and discussed for the influence of typology, construction and system in the Results and Discussion section of the report. The identified insights into solution types and the optimized use of the site are discussed in the Conclusions section of the report.

Review and Supervision

In addition to the supervising team, the help of several domain specific professionals is employed, to ensure that the design alternatives developed are plausible, and the analysis methods sound. These people, acting in their respective fields of expertise are namely:

- Caroline Stahl - Architect
- Ralf Ziegler - Technical System Planner
- Prof. Gillaume Habert - Professor of Sustainable Construction
- Arne Löffler - Cost Planner

The supervising team is composed of Instructor Hannes Reichel, as the direct supervisor of this master thesis and well as examing professors Prof. Sacha Menz, of the Chair of Architecture and Building Process and Prof. Dr. Arno Schlüter, of the Chair of Architecture and Building Systems.

Site

Behringstrasse 36, Berlin-Treptow

Zone	Residential (W2)				
Plot Width	7.80 m	Building Width	7.80 m	Eave Height	7.85 m
Plot Length	38.6 m^2	Building Length	10.80 m	Ridge Height	10.75 m
Plot Area	301 m^2	Building Footprint	84.2 m^2		

Built Area Plan

Situation Plan Proposed

Aerial Perspective (Initial)

Treptow benefits from being close to the Spree, the main river running through Berlin, as well as being home to Treptower Park, one of the city's largest parks both a place of recreation and tourist destination. Since a municipal reform in 2001 the borough is referred to as Treptow-Köpenick and now represents almost 20% of the surface area of berlin. At the west most tip of the borough, the built environment has a dense urban structure which gradually becomes suburban as one moves eastward.

As a result of the site's proximity to the Spree, it finds itself in a groundwater protection area. Electricity, water, sewer and gas network are available at the site, however district heating is not available. Berlin makes use of a single pipe sewer system for grey and black water.

The site is located in a residential area with a W2 classification, though interspersed with some commercial constructions. The parcel is long and narrow measuring 7.8m by 38.6m at an orientation 40° South-West.
The short rear side of the parcel is directly adjacent to the rails of the Berlin S-Bahn (public transport) and of the Deutsche-Bahn (heavy transport). Access to the parcel is provided over a cobble stoned street. The right side of the parcel touches onto a continuous row of houses, and the left onto an empty lot as several buildings on this street were destroyed during or after WWII including the building which previously stood on the site in question. Since this time, only several small single car garages of wood construction had been erected at the site. At the time of beginning the study the garages were essentially ready to be removed to allow for a new development to begin.

The closed construction style of the neighbourhood requires that houses be built directly adjacent to their neighbours creating a continuous construction line both on the street and garden side. The footprint of the new construction is therefore 7.8m x 10.8m. The construction line is at 5m from the edge of the street side of the plot. A small garden with a fence is to be kept at the front of the property.

As the neighbourhood has no defined construction plan (Bebauungsplan), § 34 of the Berlin building code is invoked which requires that new constructions mimic their neighbours in their dimensions and form [12].
This condition determines the height of the roof eave and ridge of the new construction (7.6m and 10.75m respectively) as well as the roof style (slope at 4° to the rear). Defining the height of the building also effectively defines the number of floors, in this case not more than one basement level, two full floors and one attic level.
Due to the noise of passing rail traffic, high quality windows are required by the local construction authority.
It is foreseen that the currently empty neighbouring lot will also be developed in the near future, though not in combination with the project under consideration.

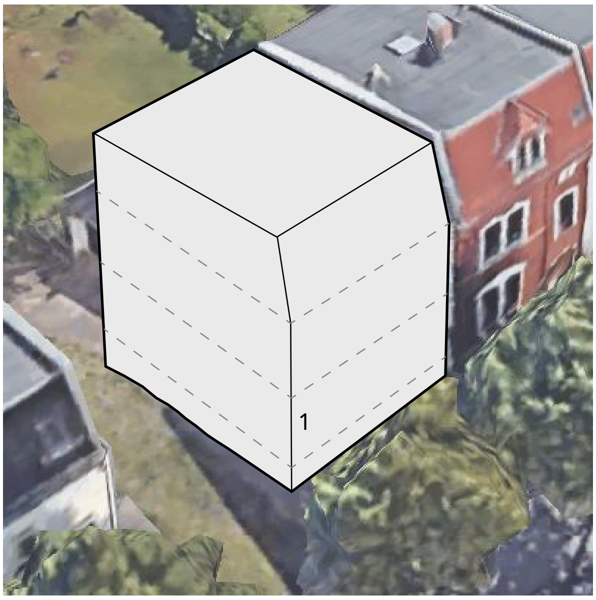
A unique feature of the site is the large garden area at the rear of the plot which is not to be developed. Nonetheless, due to the closed construction style of the neighbourhood, there is no way to access the garden but through the building itself. The plot is sloped so that the basement level of the building is exposed on the garden side.

Behringstrasse is home to a kindergarten and a seniors residence within 200m of the site and is a perpendicular to Baumschulenweg, a commercial street and road traffic artery. A sizable Berlin technical high-school (Hochschule für Technik und Wirtschaft Berlin) is also situated close by.

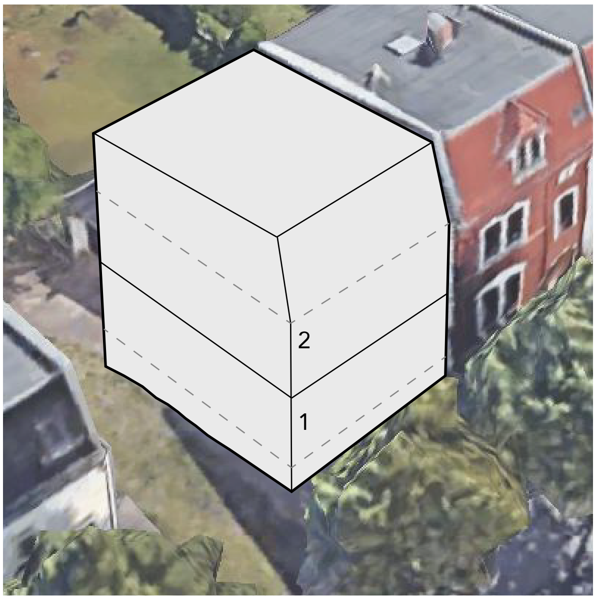
Design Alternatives

Typology

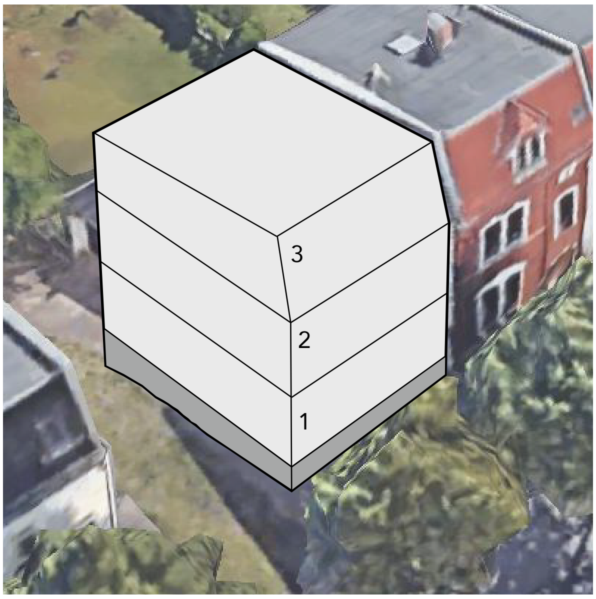
Typologies	4	Full Floors	2	Attic Livable	yes
Total Floors	4	Attic Levels	1	Basement Livable	partially
Buildable Area	337 m^2	Basement Levels	1	Building Code	§ 34 BauGB



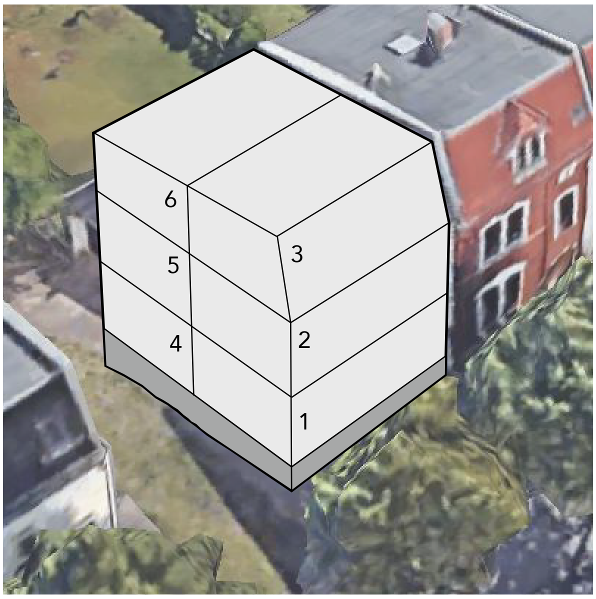
Coop-House



Multilevel Units



Flats



Mini-Apartments

Coop-House

The concept of the Coop-House refers to an undivided unit which offers private and shared spaces for a living community. The Coop-House benefits from a larger kitchen, a heated basement with a living room and access to the garden for all the residents. Some examples of potential Coop-House users could be singles or couples, students or young professionals. A single rental agreement would be arranged for the entire house, keeping management costs low.

Multilevel Units

The two Multilevel Units, sometimes referred to as a ‘Maisonette’ or a ‘Townhouse’, are designed so as to each have access to two floors of the building. The lower unit is comprised of the basement and ground level of the building, while the upper unit consists of the upper two levels of the building. Due to the need for circulation space, the lower unit is smaller than the upper unit, however the lower unit has the benefit of garden access, which the upper unit does not. This typology could easily accommodate families and potentially shares of students of the local high-school.

Flats

The Flats are typical apartments representing a base case for the typology parameter. With a total of three units to the building, one unit is designed per floor, on all floors except for the basement. As the basement does not offer living space, it is not heated, though it could be used for storage, a shared hobby or laundry room, as well as garden access for all of the building’s residents. The Flats are appropriate for singles, couples, flat-shares and small families.

Mini-Apartments

The Mini-Apartments serve as divided living spaces for students, travellers or singles. In one room, each of these units provides a kitchenette, a single bed and closet, a study or work space, as well as a separate private bathroom. Six Mini-Apartments can be arranged within the building, with two units per floor on the upper three floors. As in the case of the Flat typology, the basement is unheated and reserved for storage, a shared hobby or laundry room, and garden access for all.

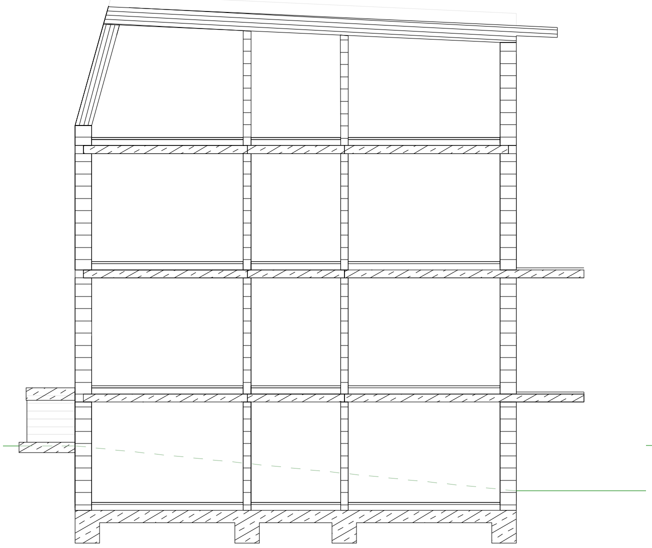
Construction

Two construction concepts are defined as Masonry and Wood which are inspired from ‘natural’ material families, mineral and wood fibre. Wherever possible, the individual building components incorporate materials from these families. For both constructions, glues and polymer based insulation are avoided. Reference material for these concepts is provided by material producers Ytong/Silka and NurHolz. The Masonry and Wood constructions were selected in part for their contrasting qualities presented in the Construction Concept Comparison Table [13].

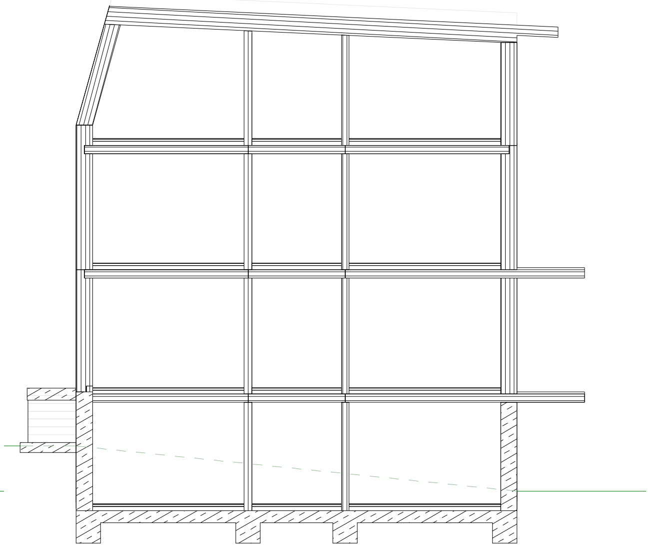
Construction Concept Comparison

Masonry	Wood
- Greater thermal storage capacity - Lower infiltration - Higher embodied energy - Slower on-site construction - Lower cost	- Better insulated - Higher infiltration - Lower embodied energy - Prefabrication easier - Higher cost

A further goal is to strike a balance between high thermal insulation, or lowest overall heat transfer coefficient (U-value), and wall thickness, so as to not infringe excessively on the rentable area of the building. In order to do so, general thickness limits were set for the various components of the envelope and otherwise. Front and rear exterior walls were allocated around 40cm, exterior side wall 33cm, below grade walls 45cm, unit separating walls 25cm, interior load bearing walls 17cm, simple separating walls 13cm, and finally ceilings 35cm. The Construction Concept Diagrams show generally how the main construction materials are assigned to the building components per construction.



Construction Concept Masonry



Construction Concept Wood

The Masonry construction is considered the base case as it is commonly applied in multifamily residential developments in Berlin. For this construction, the structure is provided by limestone blocks of varying thickness. For above-ground applications, insulation is achieved with solid mineral insulating blocks applied as an exterior layer in a WDVS configuration [14]. As a result, the walls of the Masonry option are constructed on site. Ceilings are delivered as partially prefabricated reinforced concrete slabs which are integrated on site and secured with a layer of poured concrete. The Masonry construction borrows the roof from the Wood construction with a layer of mineral wool instead of wood fiber performing as insulation.

The Wood construction is based on prefabricated stacked wood panels bound by wooden screws without glue, which can be formed into walls, ceilings and roof. The panels can be produced in a variety of thicknesses and insulating qualities. Exterior walls are combined with an additional layer of wood fibre insulation within a framed construction. The roof is constructed from a prefabricated panel with an additional layer of wood fibre insulation within a structure similar to the exterior walls [15].

In both cases, the basement slab is made from poured concrete. The slab can be finished in one of two ways – with or without floor heating – depending on the typology.

A particularity to the site: as the currently empty neighbouring lot is expected to be developed in the near future, the side wall of the building (initially acting as an insulated exterior wall) was accepted to have less insulating material, as in this scenario it would be transformed into a unit separating wall, no longer forming part of the envelope.

The building envelope is comprised of the external walls, external side wall, roof and basement slab. This means that the thermal boundary is inclusive of the basement, for all typologies, whether or not the basement contains living space. As a result the floor/ceiling component of the construction does not form part of the envelope, and therefore its U-Value does not significantly influence the building performance. As a result all typologies have the same thermal boundary, and Thermally Treated Area (EBF) in this case equal to 330 m^2.

System

Technical systems are proposed and developed based on the available site resources in order to meet the demands of the building. The four system options range from a carbon intensive (and no-longer permitted as a standalone solution) Gas Boiler system, to hybrid fossil and renewable solutions including Ground Source and Air Source Heat Pumps, to an entirely fossil fuel free (at the site) system, incorporating a Solar Thermal Collector. As access to a district heating network is not available at the site, systems based on this technical option are not considered.

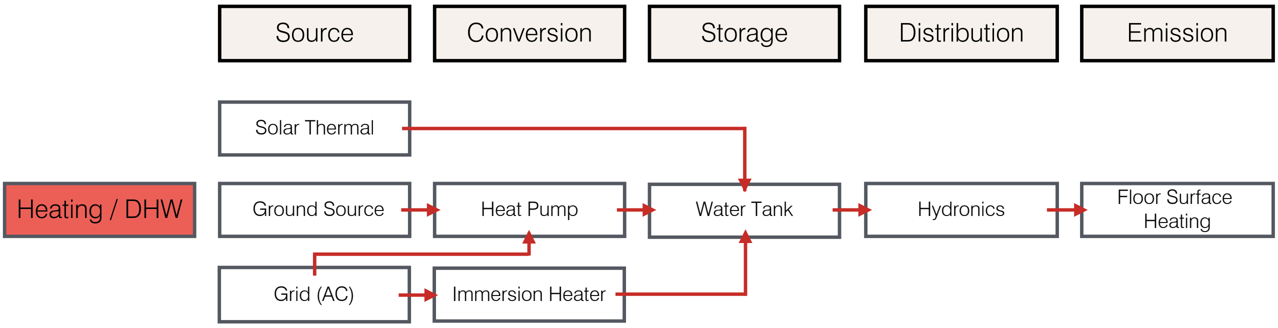
The systems supply the building's users with space heating (SH), domestic hot water (DHW), ventilation and electricity. They are defined by their energy source, conversion, storage, distribution and emission system aspects and illustrated in the System Resource Diagrams.

All the systems deliver heat to the living space of the building via a hydronic system connected to floor surface heating. Ventilation for all systems is provided via a simple window intake with extract over the kitchen and bathroom. Central ventilation potentially with heat recovery (WRG) is not considered in the study due to scope limitations.

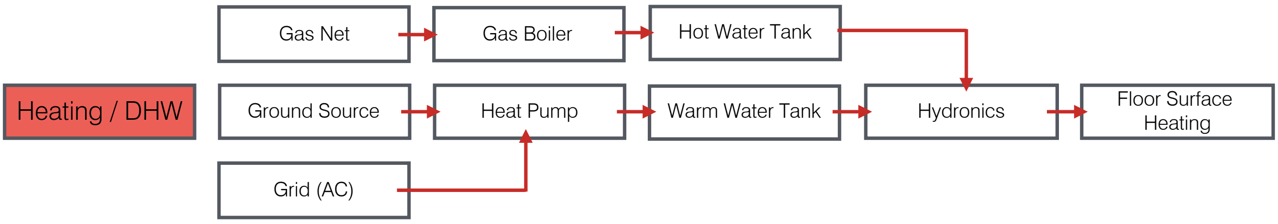
Even though some of the systems would have the potential to satisfy a cooling demand, this is not taken into consideration as residential buildings in Berlin typically do not require active cooling, particularly for common construction styles of approximately 20% window to wall ration (WWR).

For all systems electricity is provided by the city's electric grid. As the roof's main surface is sloped towards the North-West, it is not ideal for solar collection, either for electricity or heat production. Any roof mounted panels would require fixtures to orient them at a minimum horizontal and as much as possible not casting a shadow onto each other. Though in order to meet the various energy goals introduced in this study solar collection may have to play a supporting role. As the electricity grid is available at the Behringstrasse site and the heat grid is not, solar collection of heat is prioritized over electricity. As a result, photovoltaic (PV) panels are not part of any of the system options.

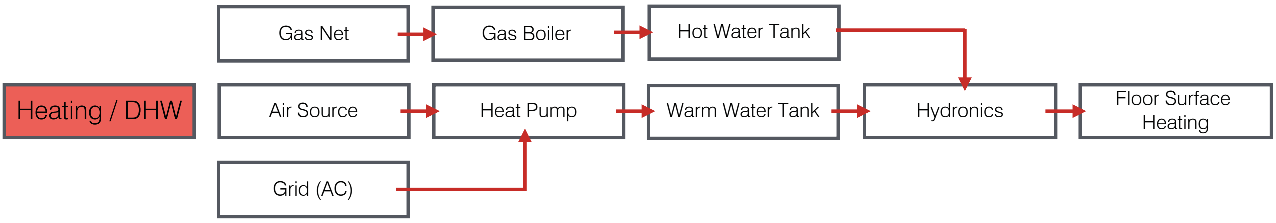
In developing the systems for evaluation, other options were considered, such as an ASHP + STC and a Wood Pellet Boiler with STC. However, the ASHP + STC was removed from the study due to it not having a reliable energy source if the outside temperature drops significantly and the sun is not shining. The Wood Pellet Boiler + STC system was also removed due to it requiring additional installation space for fuel and water storage which is not economical given the small footprint of the building.



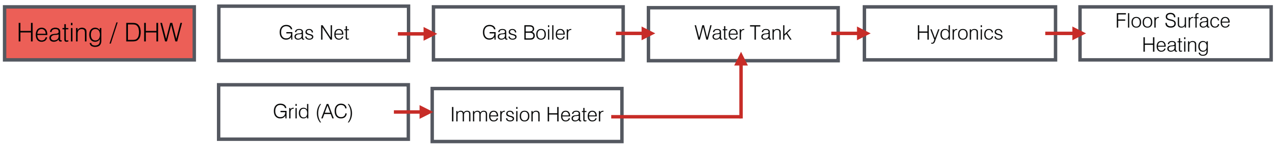
GSHP + STC System Resource Diagram



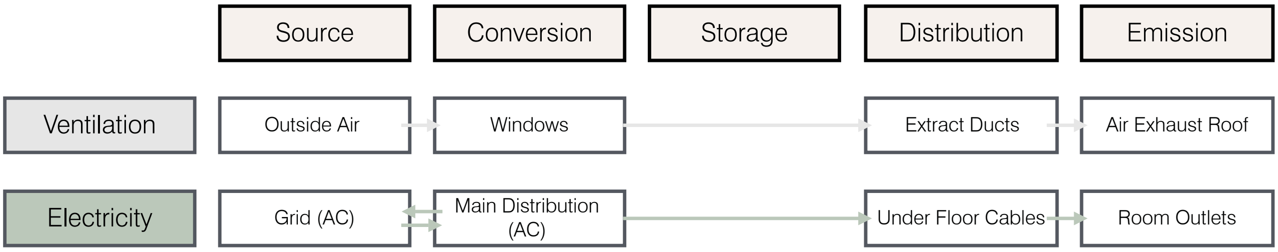
GSHP + Gas System Resource Diagram



ASHP + Gas System Resource Diagram



Gas Boiler System Resource Diagram



Ventilation and Electricity General System Resource Diagram

Ground Source Heat Pump + Solar Thermal Collector System

The heat producer of this system is a Ground Source Heat Pump (GSHP) which is connected to a double U-type vertical earth probe to be able to access a reliable ground heat source. The system is supported by a Solar Thermal Collector (STC) which heats water via the sun's radiation on roof mounted panels. The system is connected to a single large hot water storage tank fitted with an electric emersion heater as a backup heat source.

Ground Source Heat Pump + Gas Boiler System

This system uses both a Ground Source Heat Pump (GSHP), connected to a vertical earth probe, and a separate Gas Boiler to produce heat. Given the different output temperature of the two pieces of equipment, the system is arranged around two hot water storage tanks, one for SH and one for DHW. The GSHP can satisfy much of the space heating demand and act as a preheat function for the Gas Boiler which can reach DHW temperatures more effectively.

Air Source Heat Pump + Gas Boiler System

This system uses both an Air Source Heat Pump (ASHP) with access to exterior environmental air as well as a Gas Boiler to produce heat. During the coldest months of the year, when the ASHP struggles to extract heat from the environment, the Gas Boiler can handle both SH and DHW. Given the different output temperature of the two heat producers the system is arranged around two hot water storage tanks, one for SH and one for DHW.

Gas Boiler System

The Gas Boiler is the single heat producer of the base case technical system. As the Gas Boiler can deliver high temperatures with a fast response time, it only requires a small hot water tank. The hot water tank is also fitted with an immersion heater to be able to top up the tank temperature.

Analysis Method

The design alternatives are developed beyond their initial definition and gain their full detail in this section of the study. For each step of the Analysis Method sample calculations, required assumptions, localized results, as well as explanations to their handling are provided.

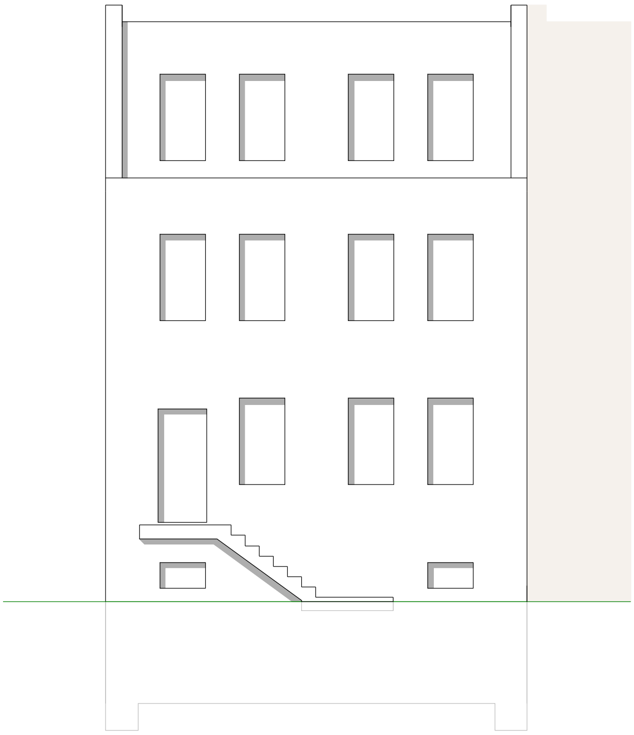
Plans

The typologies are drawn in plan, elevation and section within the constraints of the building volume and with the user, construction and system requirements in mind. The plans are intended to prove the viability of each typology, and provide the rentable areas and material requirements for construction.

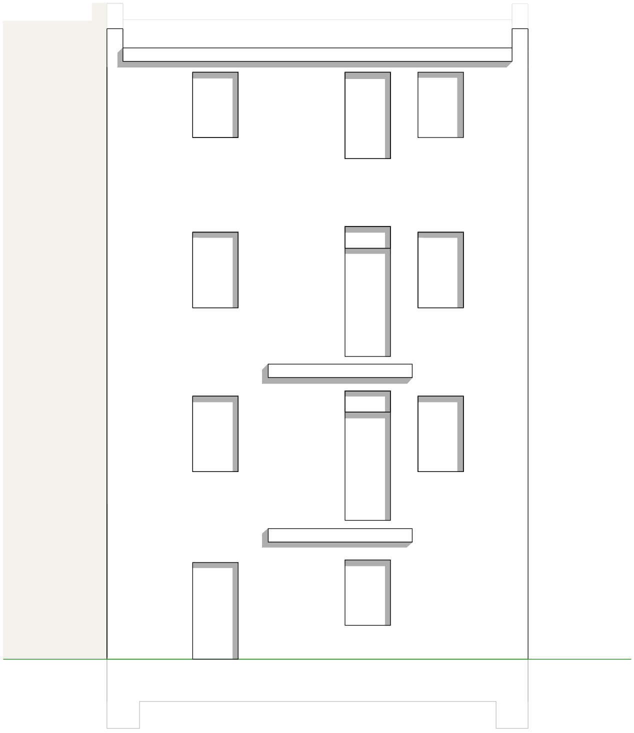
In order to help make sure that the plans generally conform to local construction regulation they have been reviewed on several occasions with Berlin based architect, Caroline Stahl [36].

For each typology, a single set of plans independent of construction and system is presented. This is possible, as it is assumed that, as the demands on the structure of the building are unexceptional, both the Masonry and the Wood construction can be applied as shown earlier in the Construction Concept Diagrams. The plans are drawn with average wall thicknesses as described in the construction section of the report, with each wall type denoted by colour. Furthermore, given that the space and installation requirements of each system are comparable, all typologies have the potential to accommodate all systems.

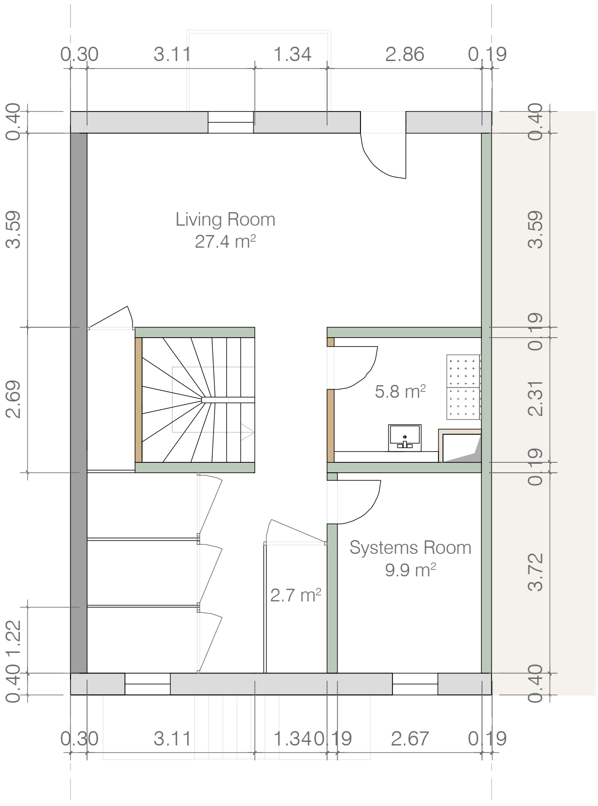
Plans Coop-House



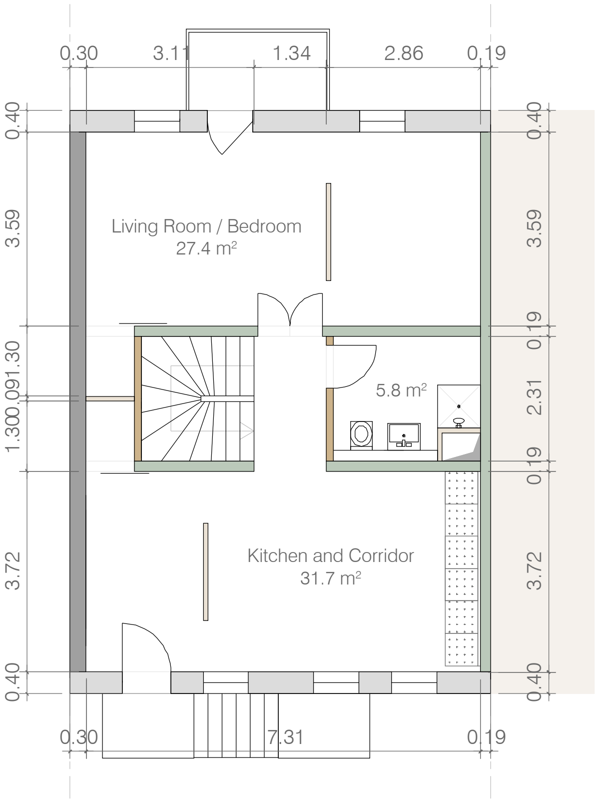
Street Elevation



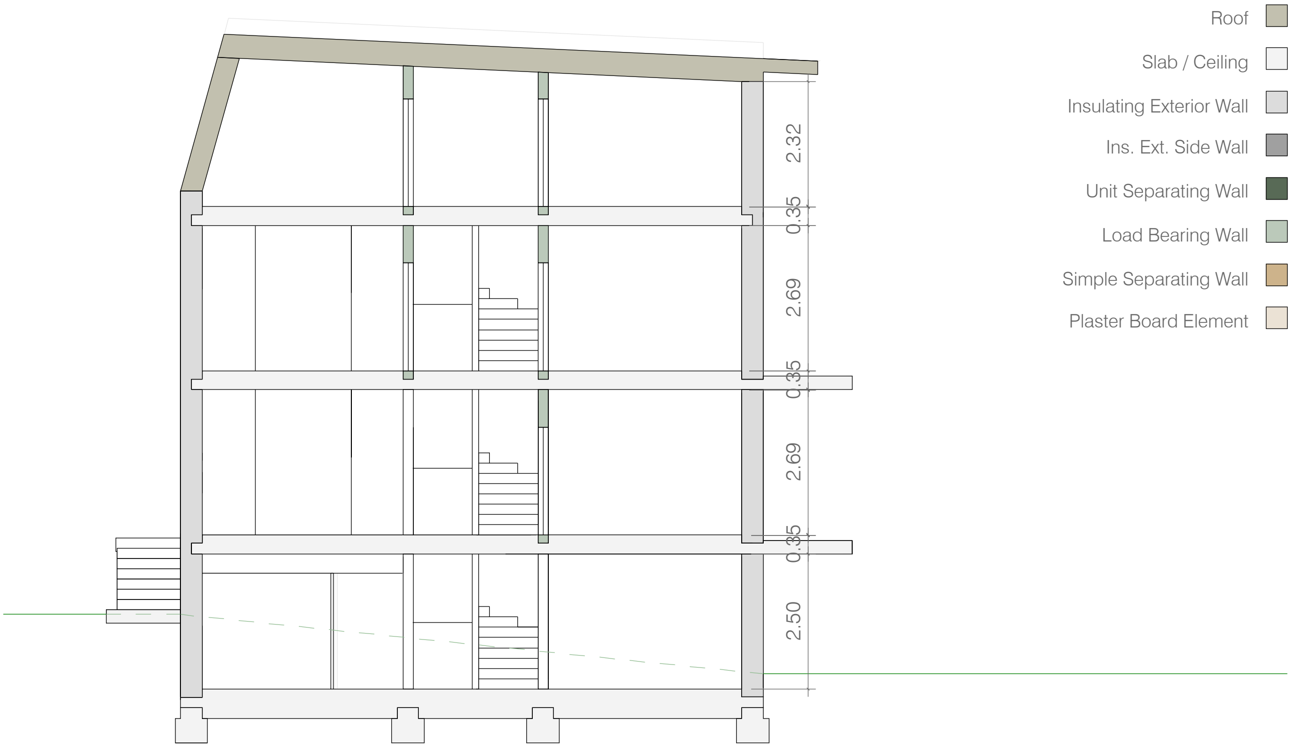
Garden Elevation



Basement Plan (KG)

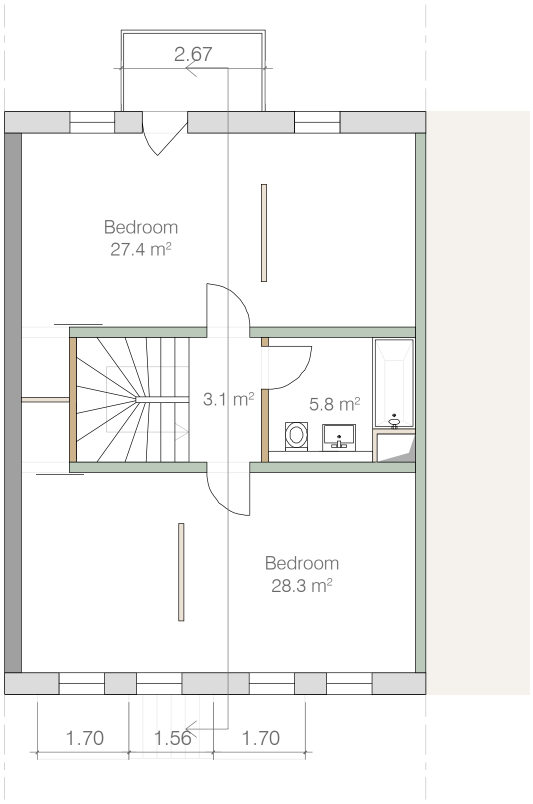


Ground Floor Plan (EG)

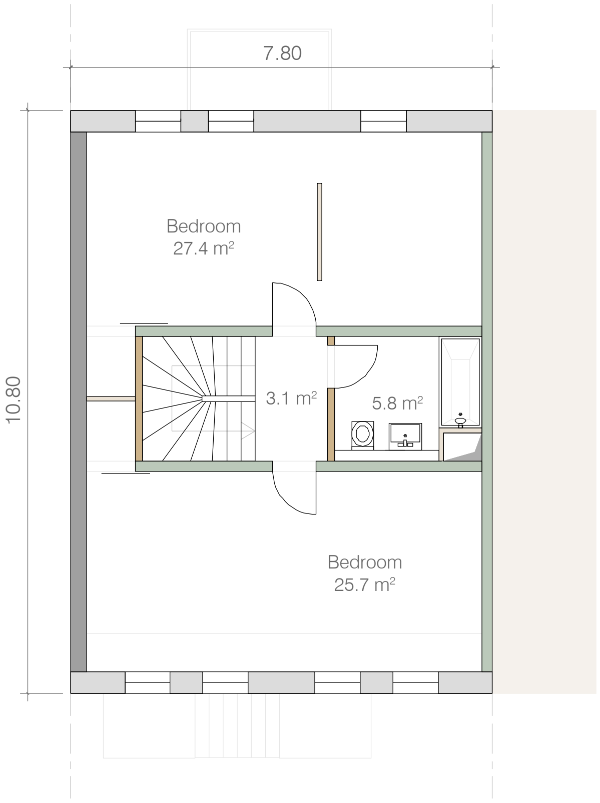


Roof ▨
Slab / Ceiling ☐
Insulating Exterior Wall ☐
Ins. Ext. Side Wall ■
Unit Separating Wall ■
Load Bearing Wall 🟩
Simple Separating Wall 🟫
Plaster Board Element ☐

Long Section



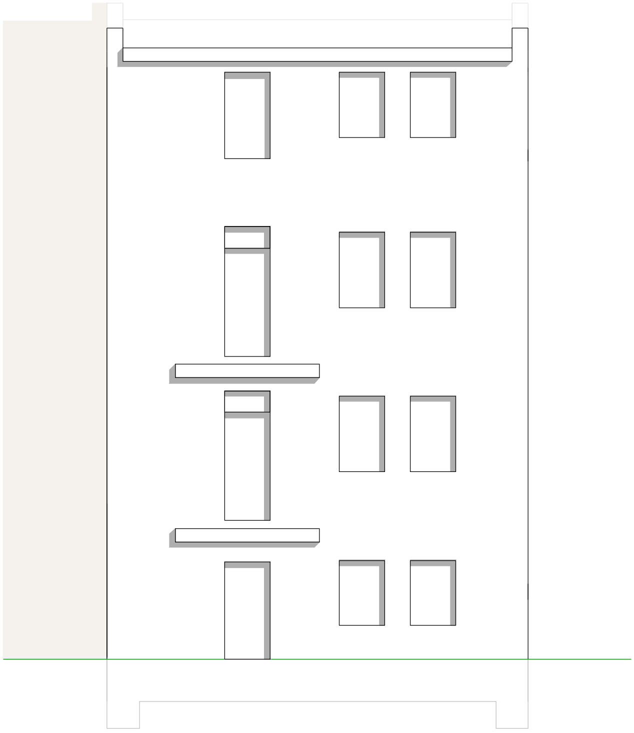
First Floor Plan (1.OG)



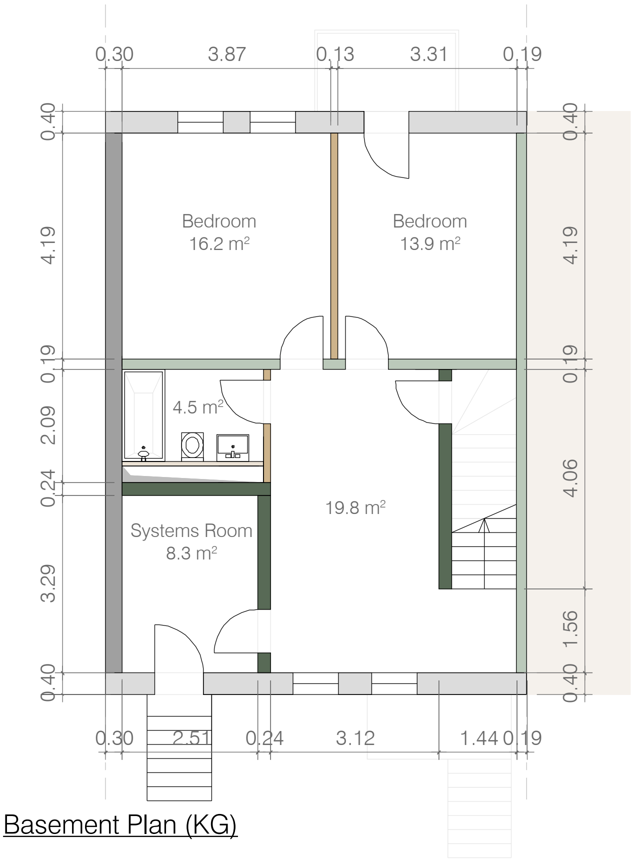
Second Floor Plan (DG)

Plans Multilevel-Units

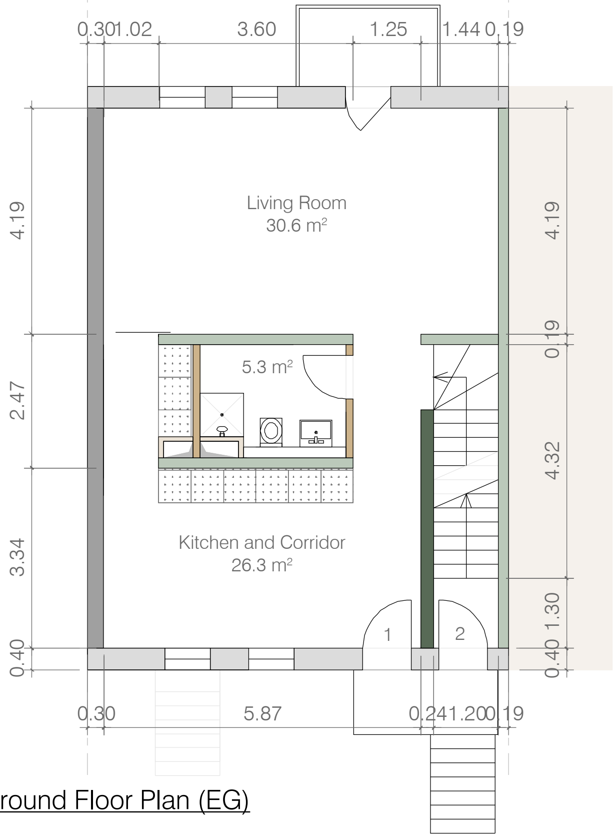
Street Elevation



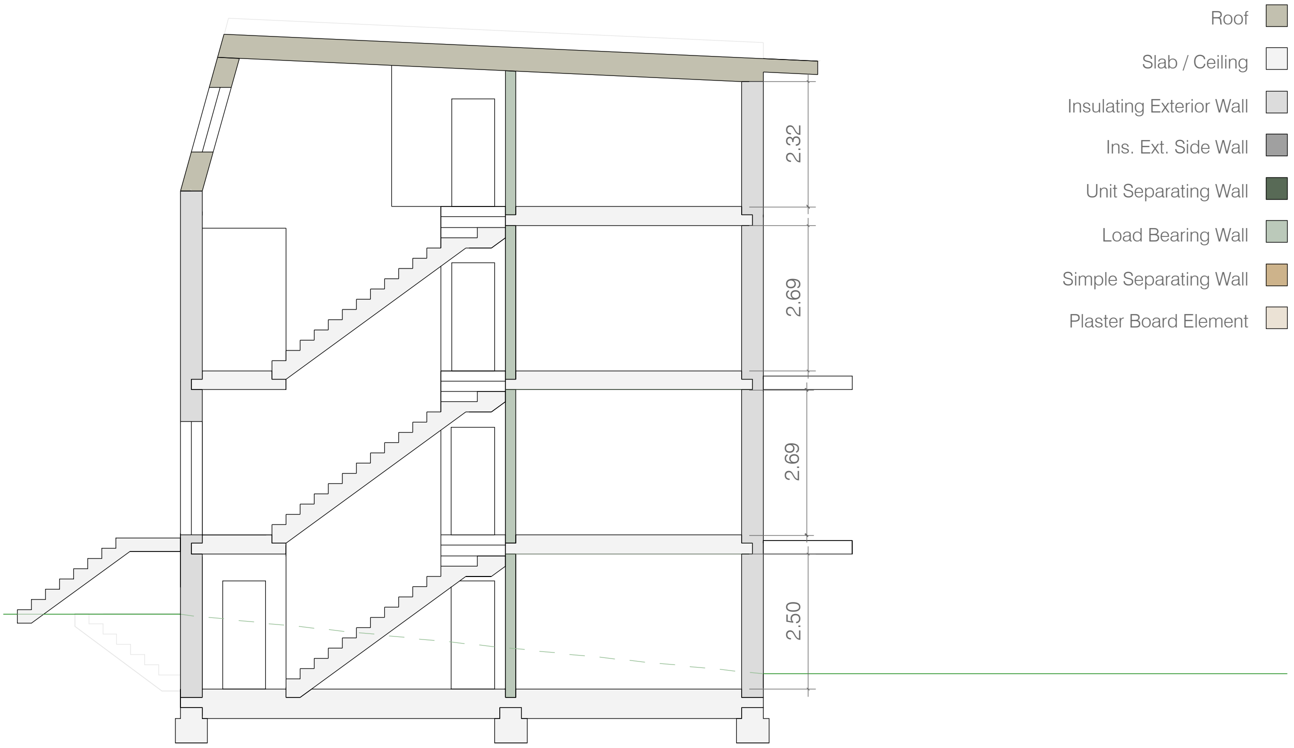
Garden Elevation



Basement Plan (KG)

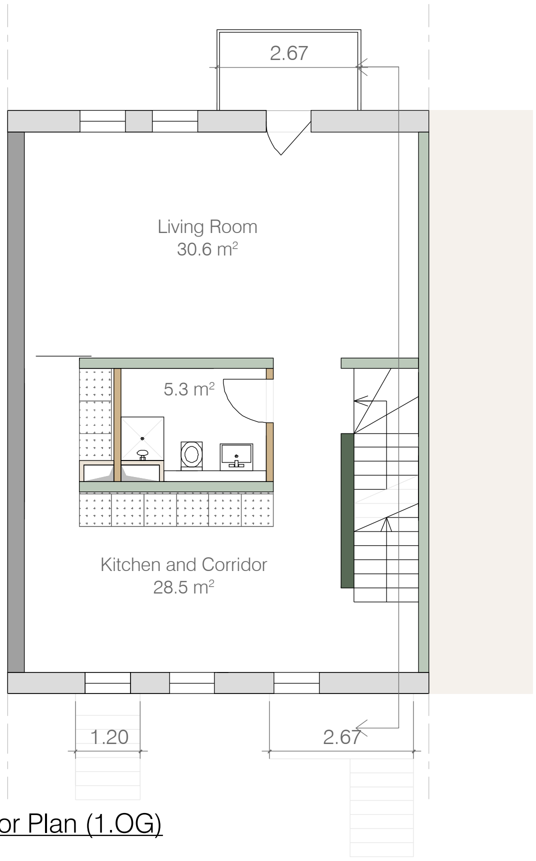


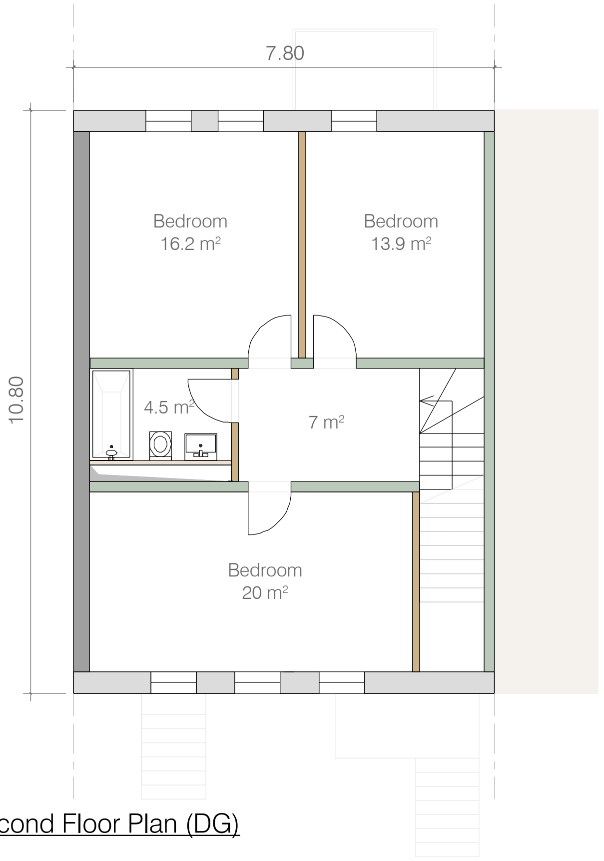
Ground Floor Plan (EG)



Roof 🟫
Slab / Ceiling ⬜
Insulating Exterior Wall ⬜
Ins. Ext. Side Wall ⬛
Unit Separating Wall 🟩
Load Bearing Wall 🟩
Simple Separating Wall 🟫
Plaster Board Element ⬜

Long Section

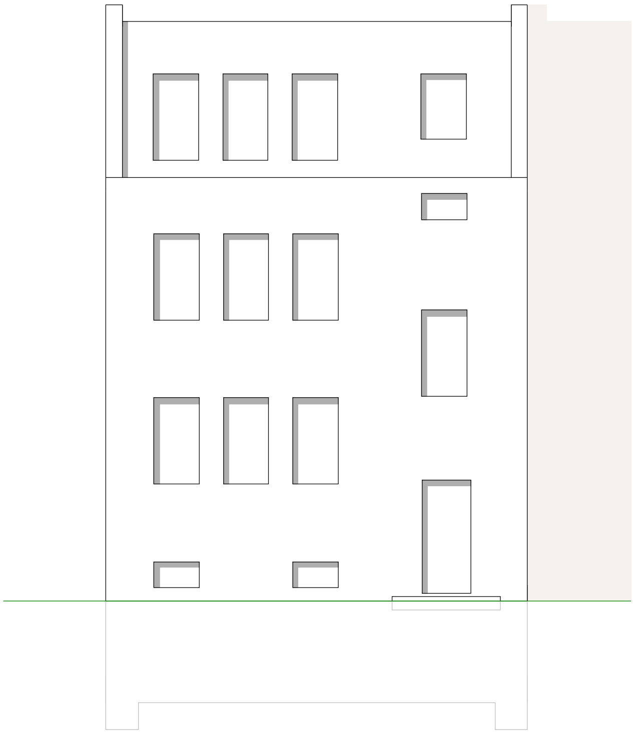




First Floor Plan (1.OG)

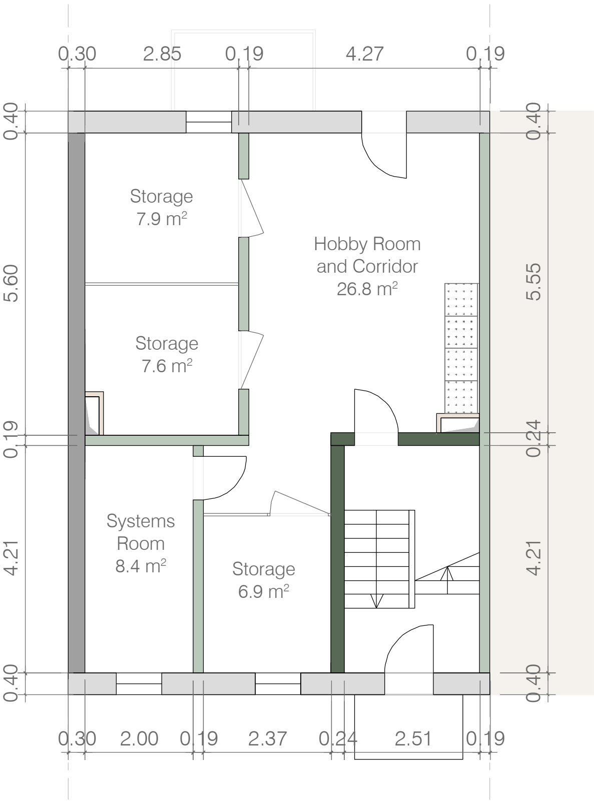
Second Floor Plan (DG)

Plans Flats

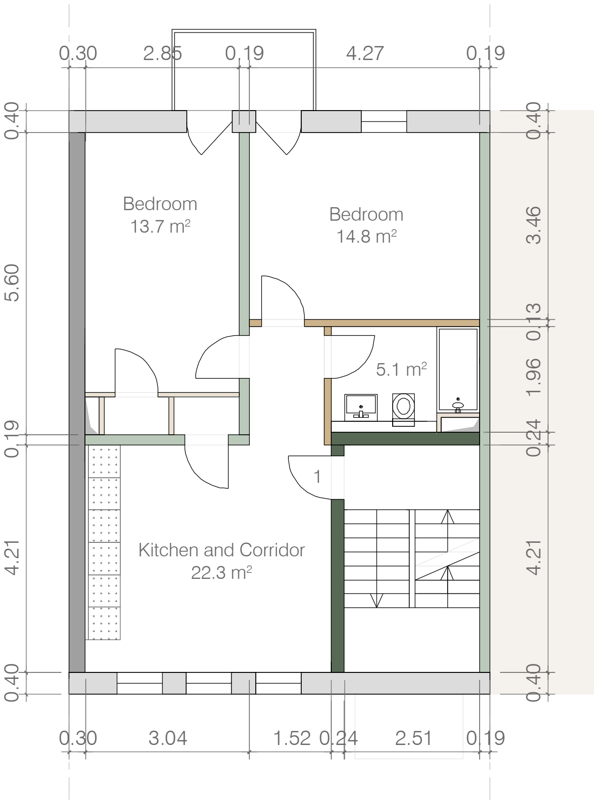


Street Elevation

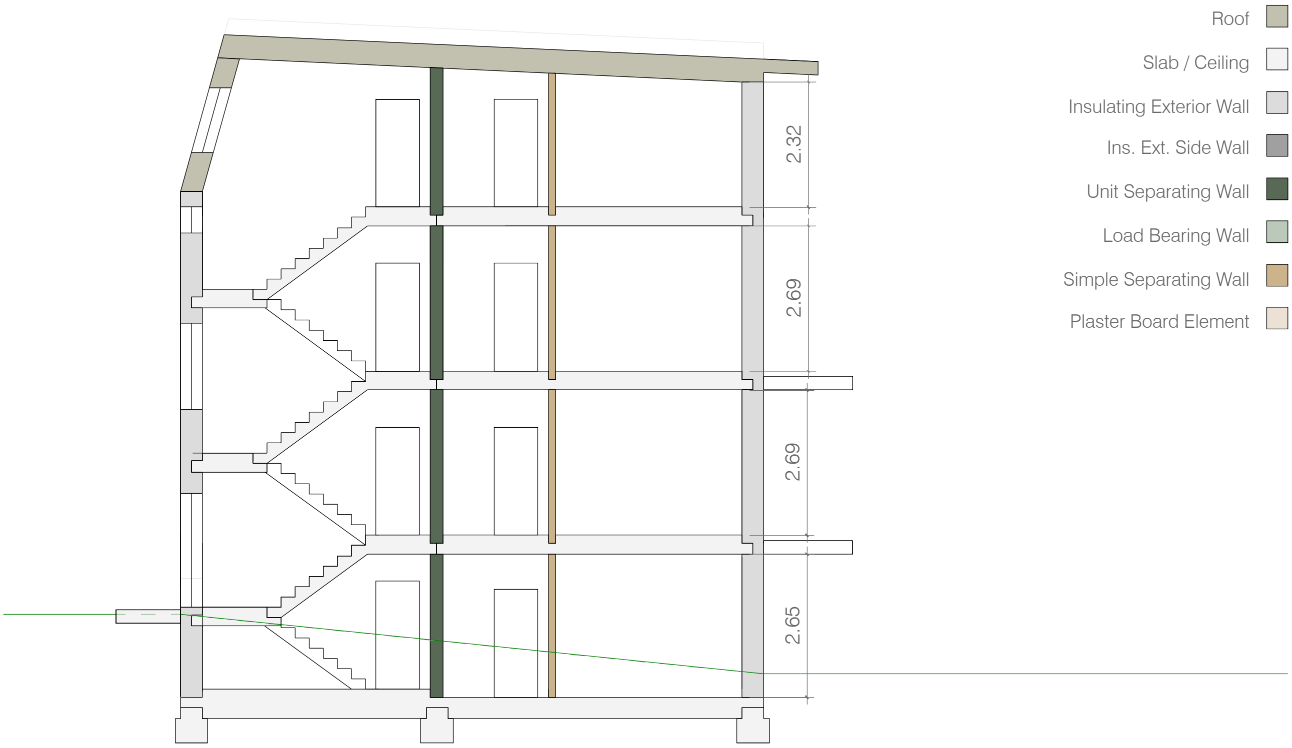
Garden Elevation



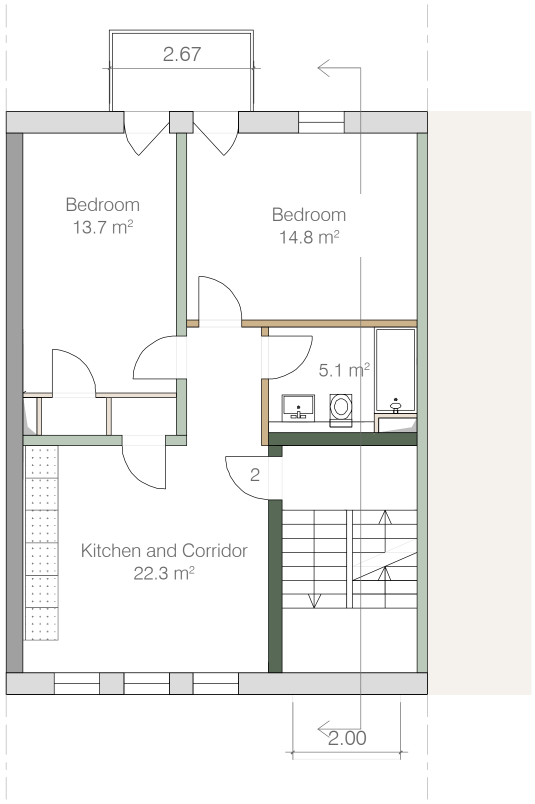
Basement Plan (KG)



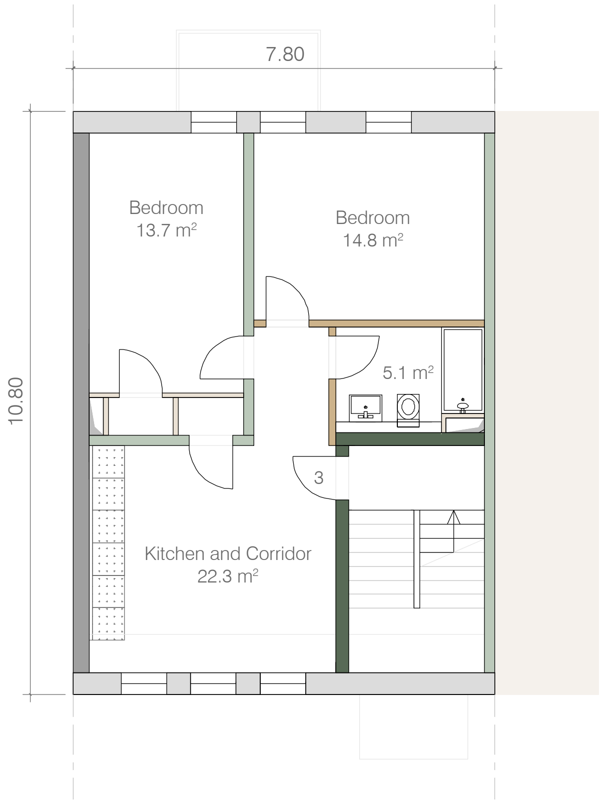
Ground Floor Plan (EG)



Long Section

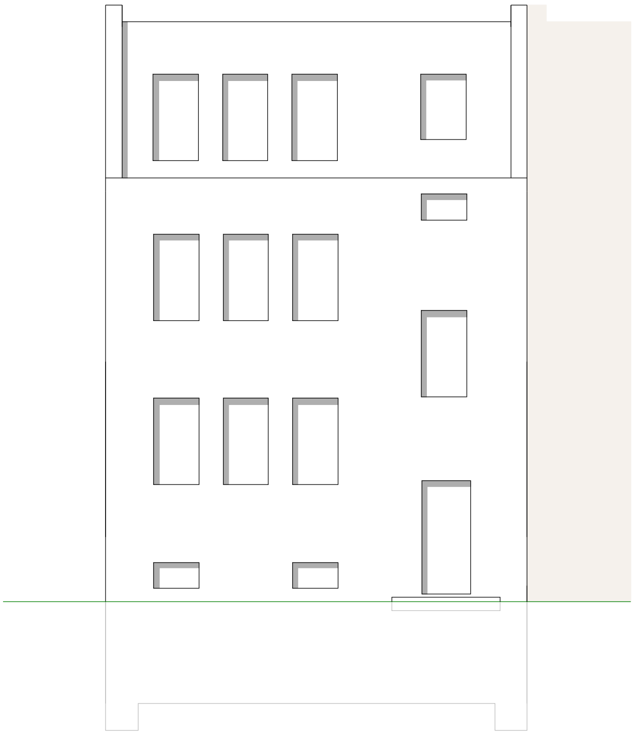


First Floor Plan (1.OG)

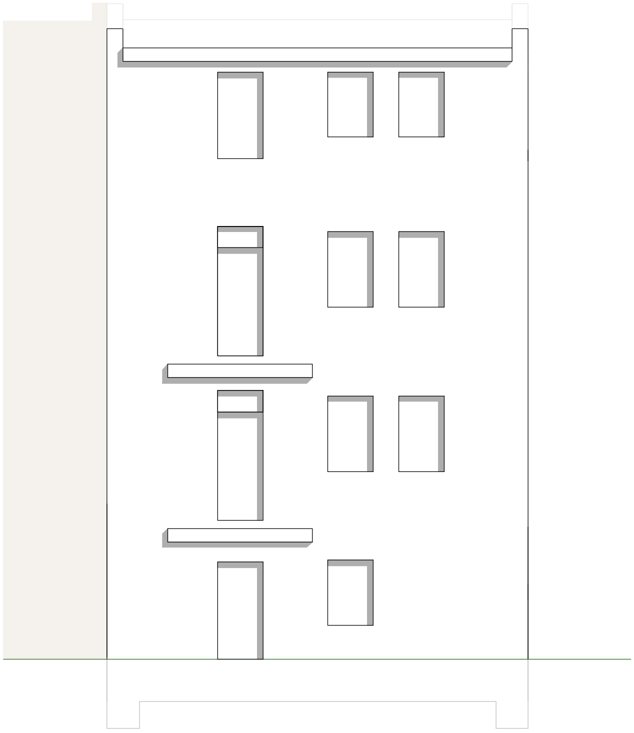


Second Floor Plan (DG)

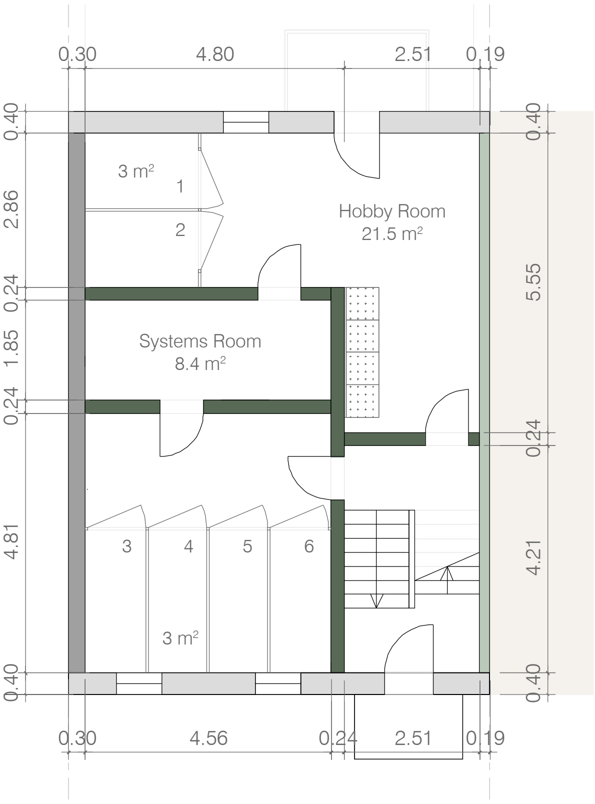
Plans Mini-Apartments



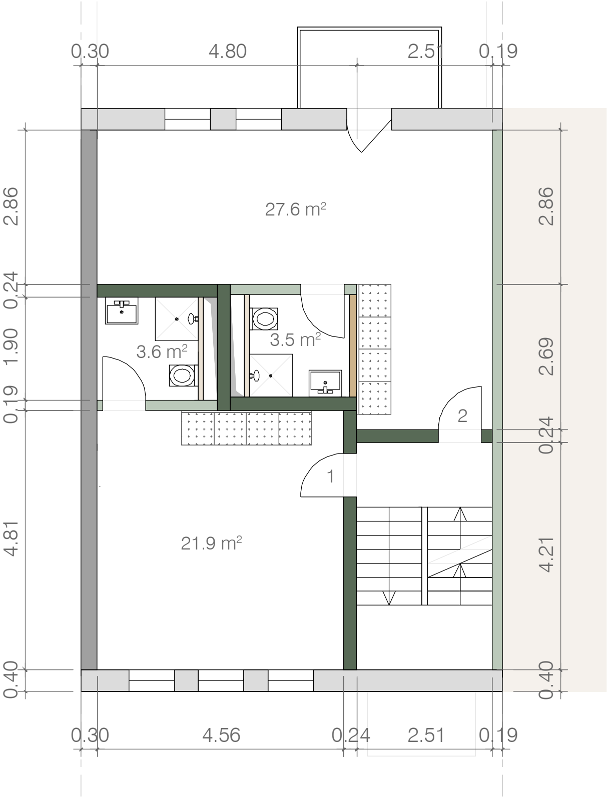
Street Elevation



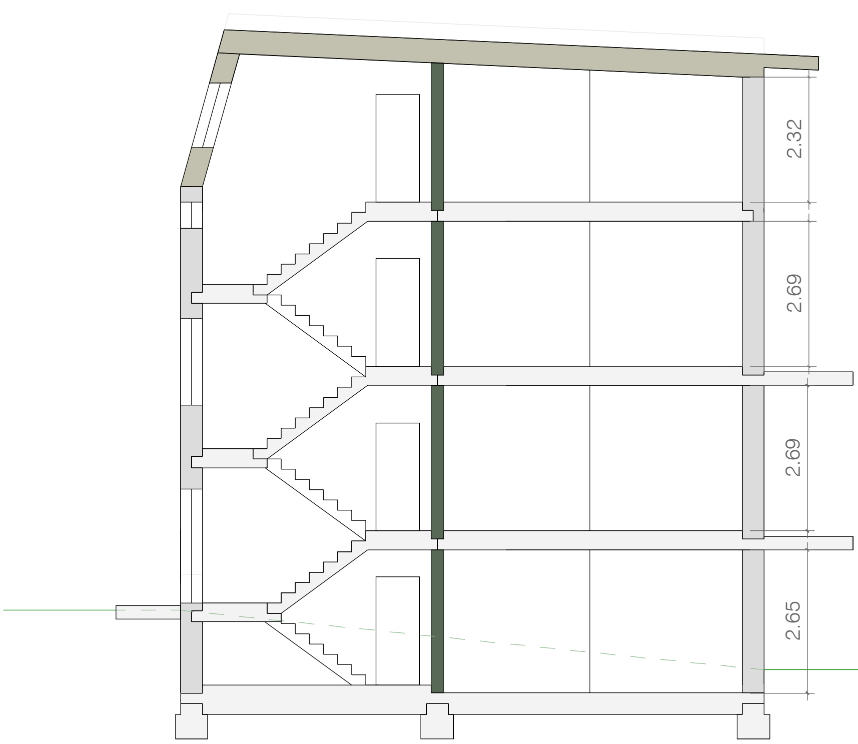
Garden Elevation



Basement Plan (KG)

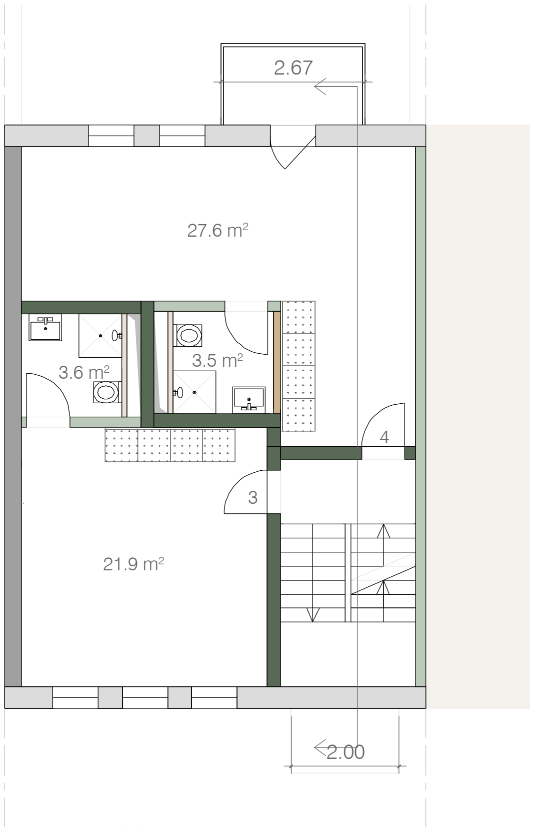


Ground Floor Plan (EG)

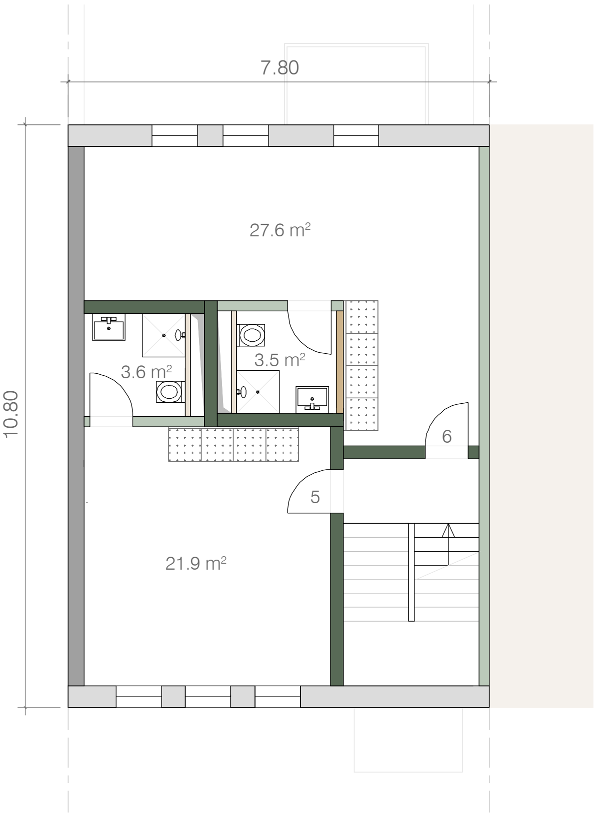


Roof ▨
Slab / Ceiling □
Insulating Exterior Wall □
Ins. Ext. Side Wall ■
Unit Separating Wall ■
Load Bearing Wall ▨
Simple Separating Wall ▨
Plaster Board Element □

Long Section



First Floor Plan (1.OG)



Second Floor Plan (DG)

Rentable Area		Coop-House	Multilevel Units	Flats	Mini-Apartments
Unit 1	m^2	240.2	116.9	58.5	25.5
Unit 2	m^2		126.0	58.5	32.1
Unit 3	m^2			56.0	25.5
Unit 4	m^2				32.1
Unit 5	m^2				23.8
Unit 6	m^2				31.1
Total Rentable Area	**m^2**	**240.2**	**242.9**	**173.0**	**170.1**
Additional Usable Area					
Common Areas	m^2			26.8	24.4
Storage	m^2			22.5	21.9
Total Usable Area and Occupany					
Total Useable Area	**m^2**	**240.2**	**242.9**	**222.3**	**216.4**
Occupancy (People)		**6**	**6**	**6**	**6**
Total Area / Person	**m^2/p**	**40.0**	**40.5**	**28.8**	**28.3**

From the plans, both the rentable areas and additional areas are calculated [16] and presented in the Rental Area and Additional Area Tables. The significant difference in the total area can be attributed to the fact that the Coop-House and Multilevel Units have contributions to rentable area from the basement level of the building, while the Flats and the Mini-Apartments do not. The occupancy for the building is derived from reading the plans, and assessing the number of occupants each typology is likely to accommodate. It is calculated that all typologies are likely to house 6 people.

Constructive measures of the first, second and third level of detail (LoD) are ascertained from the plans and tabulated in the Constructive Measures Tables. Measures of first and second LoD correspond directly to the main reference units used by the BKI [17]. Measures of the third LoD offer either further qualification to a building component's execution or simply additional information which is considered in the assessment of initial costs or embodied energy.

Constructive Measures (1st and 2nd)		Coop-House	Multilevel Units	Flats	Mini-Apartments
Built Volume (BRI)	m^3	1'053	1'053	1'053	1'053
Total Area (BGF)	m^2	337	337	337	337
Pit (BGI)	m^3	191	191	191	191
Basement Slab (GRF)	m^2	84	84	84	84
Exterior Walls (AWF)	m^2	293	293	293	293
Interior Walls (IWF)	m^2	341	360	410	366
Ceiling (DEF)	m^2	240	240	240	240
Roof (DAF)	m^2	101	101	101	101
Constructive Measures (3rd)					
Basement Slab Heated	m^2	68	55	-	-
Basement Slab Unheated	m^2	17	29	84	84
Below Grade Exterior Walls	m^2	68	68	68	68
Exterior Walls Street and Garden	m^2	122	122	122	122
Exterior Walls Side	m^2	103	103	103	103
Loadbearing Unit Sep	m^2	-	49	77	171
Loadbearing	m^2	248	216	218	147
Non Loadbearing	m^2	51	69	72	16
Plaster Board Wall	m^2	42	26	43	32
Windows	m^2	27.4	26.7	31.3	28.8
Doors	m^2	3.4	6.9	3.4	3.4
Balcony Area	m^2	7.8	7.8	7.8	7.8
Surface Heating Area	m^2	265.2	249.1	182.4	182.4

Demand Assessment

From the plans, a 3D model of the building envelope is developed in Design Builder (DB) and used to assess the SH energy demand of the building. The local climate, via a weather file for city of Berlin, as well as the neighbouring constructions in the immediate vicinity of the building, and internal gains are incorporated into the model. The output of the DB simulation is the transmission and ventilation heat losses of the envelope, as well as the annual SH demand of the building which needs to be satisfied by the system. These outputs are applied as an input in the subsequent step, where the system is examined in detail and its performance assessed.

Two versions of the building envelope model representing the Masonry and the Wood construction are developed and simulated.

The thermal characteristics and airtightness of the envelopes summarized in the Envelope Qualities Table, demonstrating how each building component satisfies the maximum EnEV values [18], are assigned to the models. As the basis for the Envelope Qualities Table, the Construction Component Diagrams and their opposing tables on the subsequent pages, show in the layering, relative thickness of materials, and resulting U-Values based on the thermal conductivity of the materials for all main building components. U-Values were calculated and diagrams generated with help of the software available on u-wert.net.

Envelope Qualities		Masonry Construction	Wood Construction	EnEV Maximum	Wood / Masonry
Front and Rear Façade	W/m²K	0.194	0.165	0.280	0.85
Exterior Side Wall	W/m²K	0.260	0.212	0.280	0.82
Below Grade Wall	W/m²K	0.179	0.185	0.350	1.03
Basement Slab	W/m²K	0.151	0.151	0.350	1.00
Roof	W/m²K	0.140	0.140	0.200	1.00
Glazing (triple)	W/m²K	0.786	0.786	1.300	1.00
Infiltration	ACH	0.650	0.700		1.08

The windows are allocated their qualities, as highly insulating triple pane window, as well as local shading for both the Masonry and the Wood models.

Airtightness and WWR values are assigned to the model. Given that the WWR for all typologies are comparable and that the amount and arrangement of the opening is not a central aspect of this study, average values for the front façade (20%) and rear façade (17%) are allocated to both of the models.

Window to Wall Ratio (WWR)	Coop-House	Multilevel Units	Flats	Mini-Apartments
Street Façade	19%	21%	21%	21%
Average				**20%**
Garden Façade	17%	15%	18%	18%
Average				**17%**

Annual DEC		Coop-House	Multilevel Units	Flats	Mini-Apartments
Unit 1	kWh	4'300	2'500	2'200	1'100
Unit 2	kWh		3'500	1'700	1'100
Unit 3	kWh			1'100	1'100
Unit 4	kWh				1'100
Unit 5	kWh				1'100
Unit 6	kWh				1'100
Total Consumption	kWh	4'300	6'000	5'000	6'600
Adjustment Factor		1.1	1	1	0.9
Total Consumption Adjusted	kWh	4'730	6'000	5'000	5'940
Average Multilevel & Mini-Apt	kWh				5'970
Average Coop & Flats	kWh				4'865

Domestic Electricity Consumption (DEC) is a heat source within the building which needs to be considered as it reduces the SH demanded of the system. The 2016 German DEC Index of residential households or 'Stromspiegel' [19] is consulted to establish the approximate DEC demand for the building users per typology, excluding DHW and SH. Efficiency class B of the Index is referenced, and an adjustment factor applied to correct the data for the typologies which are likely not accurately represented by pool of German households. DB simulations are conducted with low and high average values as calculated in the Annual DEC Table.

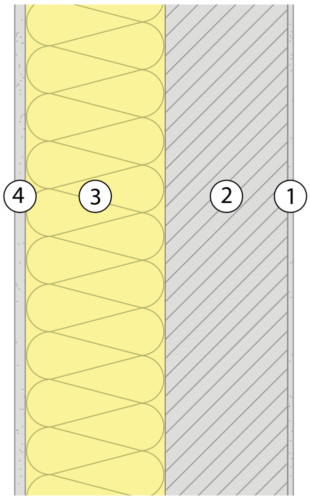
The target heating temperature of the units of 19.5°C, and if required by the typology, an unheated basement averaging 15°C, is given as an input to the simulation.

Temperature Setpoint		Coop-House	Multilevel Units	Flats	Mini-Apartments
Room Temp.	°C	19.5	19.5	19.5	19.5
Basement Temp.	°C	19.5	19.5	15.0	15.0

A total of 8 simulations are conducted in DB, one for every combination of construction and typology, for which the model is assigned a generalized heating system, as at this stage only the performance of the envelope is of interest. Also, as the preparation and consumption of DHW do not have a significant effect on the demand for SH, and because DB does not take this effect into account, DHW is left out at this stage in the analysis.

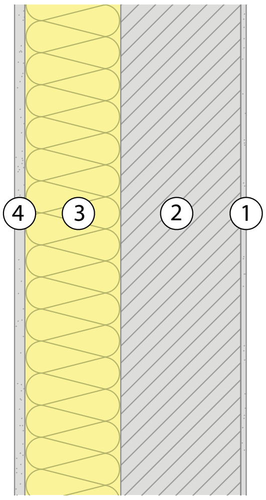
Surprisingly, the values returned from the demand simulation of the two constructions, Masonry and Wood, were comparable on a per typology basis, as shown in the DB Output Table. This means that the two envelopes (the combination of insulation and infiltration) have similar overall performance. This was not an expected result, furthermore each model was developed separately. The explanation for this is that, although the Wood construction is better insulated, its higher infiltration cancels this benefit, and in the end, makes it comparable to a Masonry construction with slightly lower insulation though more airtightness. This result helps to simplify subsequent analysis steps as a single averaged demand value can be applied per typology regardless of construction.

Demand Assessment (Masonry Envelope and Construction)



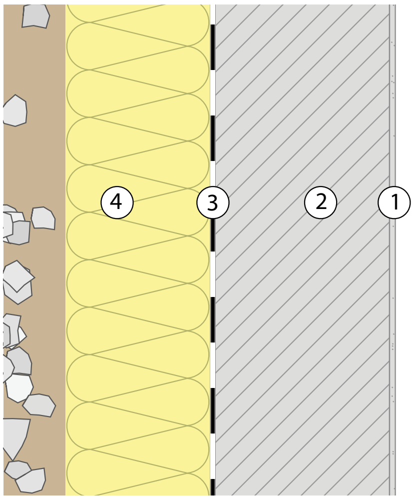
Exterior Wall

	Exterior Wall Layer	Thickness (cm)	λ (W/mK)	U-Value (W/m²K)
1	Gypsum Plaster	0.8	0.35	
2	Limestone Block	17.5	0.70	
3	Mineral Insulation Panel	20	0.05	
4	Insulating Plaster	1.5	0.05	
		39.8		0.194



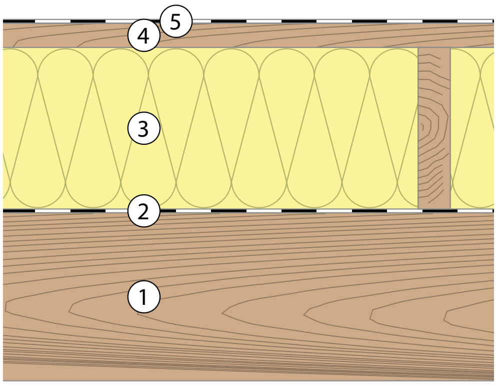
Exterior Side Wall

	Exterior Side Wall Layer	Thickness (cm)	λ (W/mK)	U-Value (W/m²K)
1	Gypsum Plaster	0.8	0.35	
2	Limestone Block	17.5	0.70	
3	Mineral Insulation Panel	14.0	0.05	
4	Insulating Plaster	1.5	0.05	
		33.8		0.260



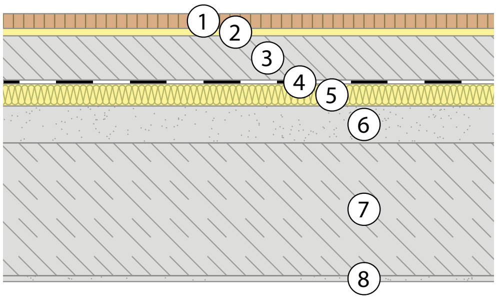
Exterior Below Grade Wall

	Ext. Below Grade Wall Layer	Thickness (cm)	λ (W/mK)	U-Value (W/m²K)
1	Gypsum Plaster	0.8	0.35	
2	Light Limestone Block (1,2)	24.0	0.12	
3	Bitumen Membrane	0.3	0.17	
4	XPS Insulation	20.0	0.04	
		45.1		0.179



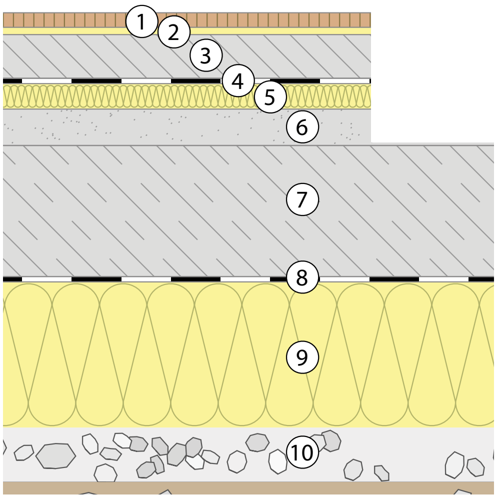
Roof

	Roof Layer	Thickness (cm)	λ (W/mK)	U-Value (W/m²K)
5	Bitumen Membrane	0.5	0.23	
4	OSB Wood Panel	3.0	0.13	
3	Mineral Wool Insulation / Joists	20.0	0.04	
2	PE Foil	0.0	0.40	
1	Stacked Wood Ceiling Element	20.8	0.09	
		44.3		0.140



Internal Ceiling / Floor

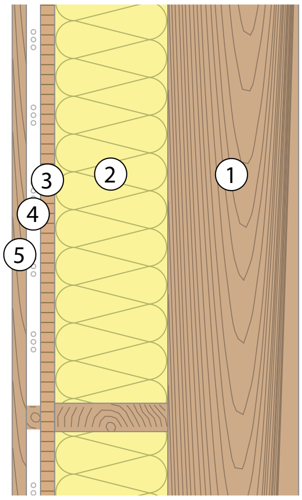
	Internal Ceiling / Floor Layer	Thickness (cm)	λ (W/mK)	U-Value (W/m²K)
1	Wood Flooring	2.0	0.13	
2	Cork Board	1.0	0.05	
3	Screed + Floor Heating	6.0	1.40	
4	PE Foil	0.0	0.40	
5	Impact Insulation	0.3	0.04	
6	Sand Leveling Fill	5.0	0.70	
7	Poured Concrete Semi-Prefab.	18.0	0.23	
8	Gypsum Plaster	0.8	0.35	
		33.1		0.600



Basement Slab

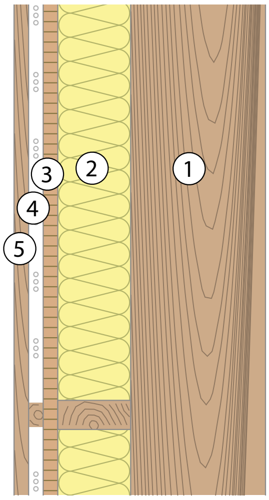
	Basement Slab Layer	Thickness (cm)	λ (W/mK)	U-Value (W/m²K)
1	Wood Flooring	2.0	0.13	
2	Cork Board	1.0	0.05	
3	Screed + Floor Heating	6.0	1.40	
4	PE Foil	0.0	0.40	
5	Impact Insulation	3.5	0.04	
6	Sand Leveling Fill	5.0	0.70	
7	Poured Concrete	18.0	0.23	
8	PE Foil	0.0	0.40	
9	XPS Insulation	20.0	0.04	
10	Pebbles	7.5	2.00	
		63.0		0.151

Demand Assessment (Wood Envelope and Construction)



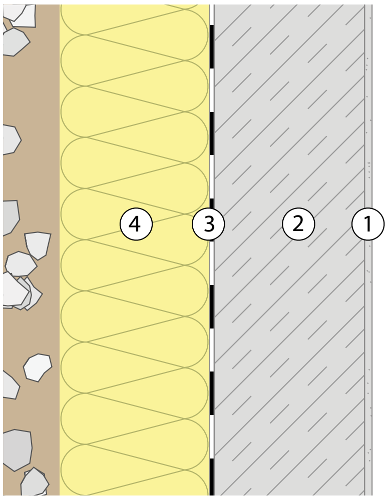
Exterior Wall

	Exterior Wall Layer	Thickness (cm)	λ (W/mK)	U-Value (W/m²K)
1	Wood Cladding	2.0	0.11	
2	Airspace	2.0		
3	OSB	2.0	0.13	
4	Wood Fiber Insulation / Joist	16.0	0.04	
5	Stacked Wood Wall Element	18.5	0.09	
		40.5		0.165



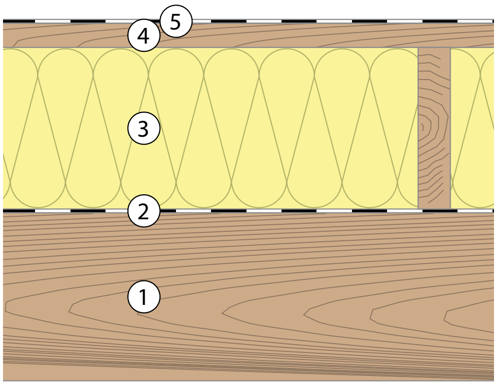
Exterior Side Wall

	Exterior Side Wall Layer	Thickness (cm)	λ (W/mK)	U-Value (W/m²K)
1	Wood Cladding	2.0	0.11	
2	Airspace	2.0		
3	OSB	2.0	0.13	
4	Wood Fiber Insulation / Joist	10.0	0.04	
5	Stacked Wood Wall Element	18.5	0.09	
		34.5		0.212



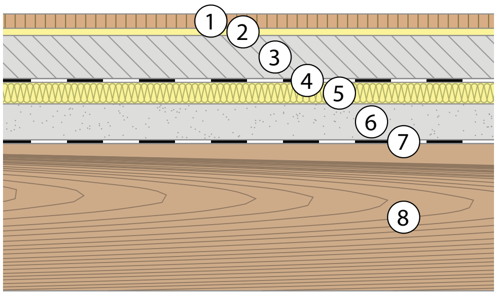
Exterior Below Grade Wall

	Ext. Below Grade Wall Layer	Thickness (cm)	λ (W/mK)	U-Value (W/m²K)
1	Gypsum Plaster	1.0	0.35	
2	Poured Concrete Wall	20.0	2.30	
3	Bitumen Membrane	0.3	0.17	
4	XPS Insulation	20.0	0.04	
		41.3		0.185



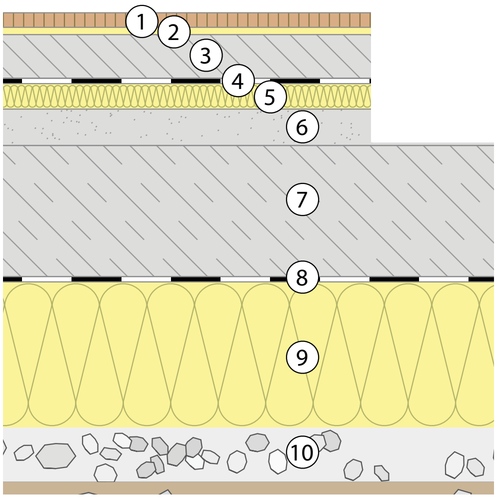
Roof

Roof Layer	Thickness (cm)	λ (W/mK)	U-Value (W/m²K)
5 Bitumen Membrane	0.3	0.23	
4 Plywood Sheet	3.0	0.13	
3 Mineral Wool Insulation / Joists	20.0	0.04	
2 PE Foil	0.0	0.40	
1 Stacked Wood Ceiling Element	20.8	0.09	
	44.1		**0.140**



Internal Ceiling / Floor

Internal Ceiling / Floor Layer	Thickness (cm)	λ (W/mK)	U-Value (W/m²K)
1 Wood Flooring	2.5	0.13	
2 Cork Board	1.0	0.05	
3 Screed + Floor Heating	6.0	1.40	
4 PE Foil	0.0	0.40	
5 Impact Insulation	0.3	0.04	
6 Sand Leveling Fill	5.0	0.70	
7 PE Foil	0.0	0.40	
8 Stacked Wood Ceiling Element	20.8	0.09	
	35.6		0.289



Basement Slab

Basement Slab Layer	Thickness (cm)	λ (W/mK)	U-Value (W/m²K)
1 Wood Flooring	2.0	0.13	
2 Cork Board	1.0	0.05	
3 Screed + Floor Heating	6.0	1.40	
4 PE Foil	0.0	0.40	
5 Impact Insulation	3.5	0.04	
6 Sand Leveling Fill	5.0	0.70	
7 Poured Concrete	18.0	0.23	
8 PE Foil	0.0	0.40	
9 XPS Insulation	20.0	0.04	
10 Pebbles	7.5	2.00	
	63.0		0.151

Annual SH Demand and Losses		Coop-House	Multilevel Units	Flats	Mini-Apartments
Heat Required - Masonry	kWh	12'251	11'656	10'979	10'382
Heat Required - Wood	kWh	12'219	11'633	10'762	10'212
Average Required Heat	kWh	12'200	11'600	10'900	10'300
Wood Transmission and Vent Losses	kWh	21'527	22'010	20'309	20'790
Masonry Trans. and Vent Losses	kWh	21'495	21'993	20'100	20'633
Average Trans. and Vent Losses	kWh	21'500	22'000	20'200	20'700

System Performance

In this step the system is modeled, and based on the SH demand of the building and other inputs, the system components sized, and its performance assessed via simulation in the Polysun software environment. Polysun is ideal for evaluating residential projects as it has a large database of equipment and templates applicable to this scale, which serve as a starting point for the modeling of this project.

Additionally at this stage, DHW consumption needs be considered. 50 l/d of DHW is assigned per occupant, therefore 300 l/d for all typologies as recommended by Polysun and verified in discussion with R. Ziegler [23].

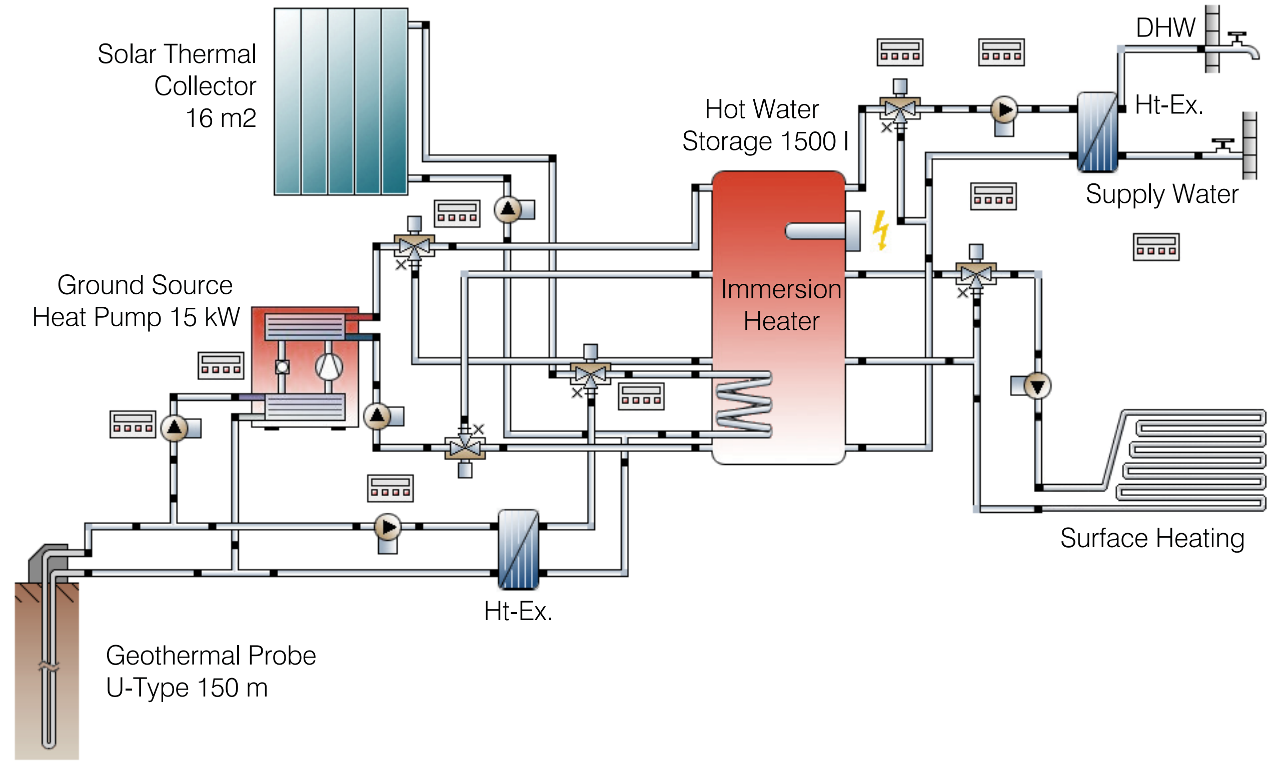
In total, 16 simulations are conducted, one for every combination of typology and system, with a single set of construction averaged demand values per typology. Through an iterative process, equipment sizing is adjusted to ensure that the system is able to deliver throughout the year with only a minimal deficit between the calculated requirement and the delivered energy. The resulting system designs have been reviewed with a technical systems planner, to help ensure that they embody practical solutions, and that possible simulations pitfalls have been avoided. A summary of the component sizes of the resulting systems are presented in the System Components Table.

System Components		GSHP, STC	GSHP, Gas Boiler	ASHP, Gas Boiler	Gas Boiler
Heat Pump Rating	kW	15	10	10	
Boiler Rating	kW		10	10	20
Earth Collector Length	m	150	150	-	-
Solar Collector Area	m^2	16	-	-	-
Hot Water Storage Volume	l	1'500	1'200	700	-
DWH Storage Volume	l	-	500	300	200
Space Requirements	m2	8	8	8	8

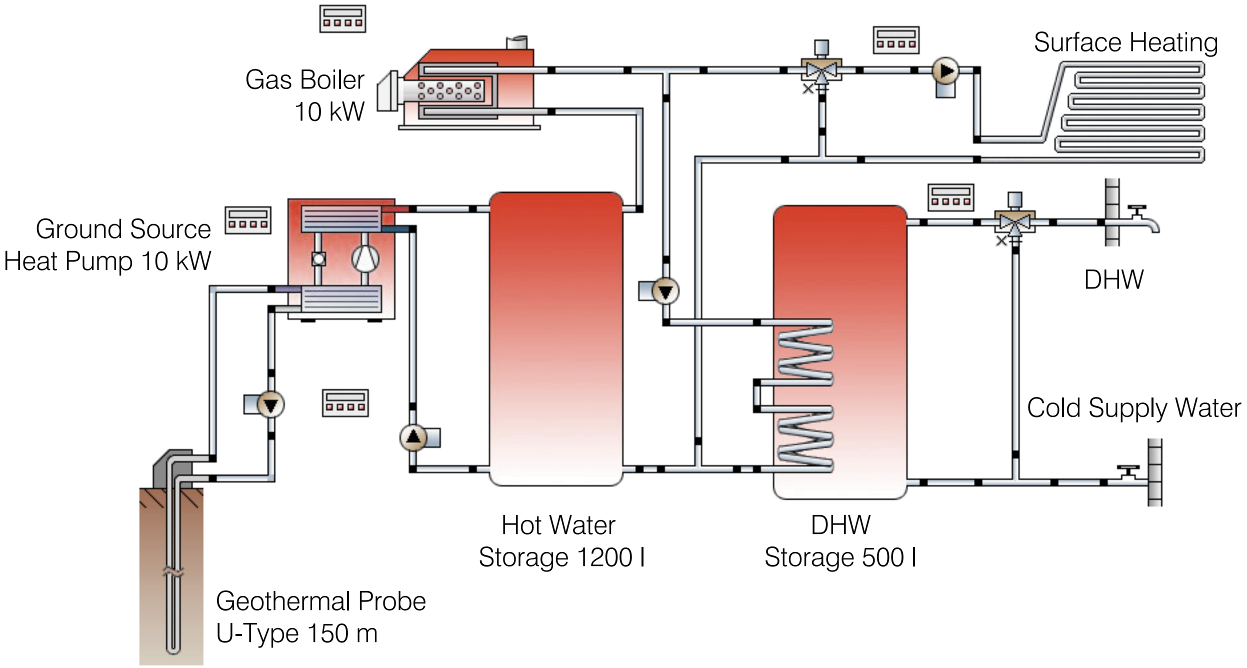
The models developed in Polysun are captured and presented as system model diagrams. These diagrams show additionally how the individual components of the system are connected.

A set of Polysun sample results for the range of systems are shown for the Flat typology in the Annual Demand Table. Outputs include the combined heat requirement for SH and DHW, the actual heat delivered for SH and DHW (useful energy), as well as the breakdown between the fuel sources in order to meet this demand (end energy). From the resulting values the effective system performance, total end energy per area, SH end energy per area, as well as the total primary energy per area [20], are computed. These values are then be checked against the various energy regulations for compliance.

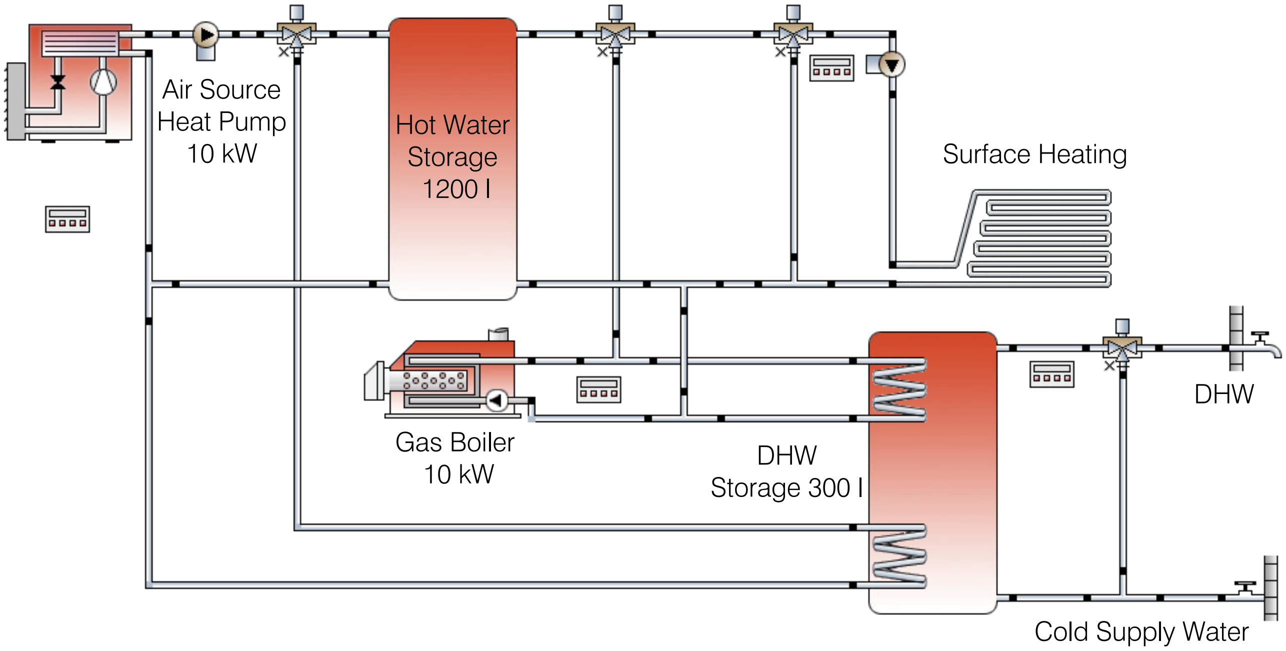
All heat pump based systems require significantly less fuel energy than the useful heat energy delivered to the users in the building. This is due to the fact that the heat pumps are able to leverage the input fuel energy, in this case with a factor of 3-5, referred to as Coefficient of Performance (COP).



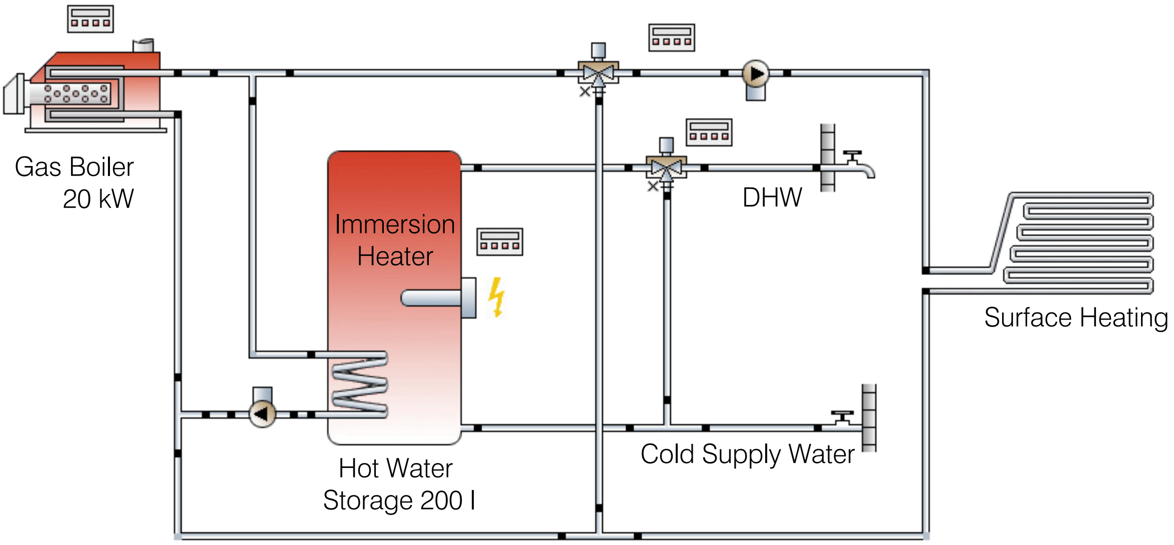
GSHP + STC System Model



GSHP + Gas System Model



ASHP + Gas System Model



Gas Boiler System Model

Annual Demand SH and DHW		GSHP, STC	GSHP, Gas Boiler	ASHP, Gas Boiler	Gas Boiler
Heat Requirement	kWh	16'084	16'084	16'084	16'084
Energy Delivered (Useful Energy)	kWh	14'816	15'860	15'949	15'904
Electricity Fuel	kWh	3'684	4'928	6'753	125
Gas Fuel	kWh	0	2'477	135	19'849
Total Fuel (End Energy)	kWh	3'684	7'404	6'888	19'974
Effective System COP		4.02	2.14	2.32	0.80
End Energy per Area (Energieausweis relevant)	kWh/m²a	11	22	21	60
SH End Energy per Area (Passivhaus relevant)	kWh/m²a	9	17	16	46
Primary Energy					
PEF Electricity Grid Mix		1.8	1.8	1.8	1.8
PEF Gas Grid		1.1	1.1	1.1	1.1
Total Primary Energy (PE)	kWh	6'632	11'594	12'304	22'059
Primary Energy per Area (EnEV relevant)	kWh/m²a	20	35	37	67

Despite having tuned all systems to the requirements of the building, the ASHP + Gas system produced unexpected results, namely the proportion of electricity to gas fuel required. The concept behind this system is that the gas boiler takes over during the coldest time of the year when the heat pump struggles to extract energy from the environmental air. Given that the winter in Berlin lasts several months, having only 2% of total fuel energy come from the gas source is therefore questionably low.

When checking the results of the system performance for the Flats against current energy regulation, it is clear that the base case Gas Boiler system does not satisfy the basic EnEV regulation and is therefore no longer permitted to be constructed in Germany. All heat-pump based systems pass the basic German regulation, while the GSHP + STC System satisfies the KFV 40 goal and moreover qualifies as a Passivhaus.

EnEV 2016 Primary Energy limit for a reference building is calculated with a simplified method [21].

Energy Regulation		GSHP, STC	GSHP, Gas Boiler	ASHP, Gas Boiler	Gas Boiler
EnEV 2016 PE Limit (Approx.)	kWh/m²a	40	40	40	40
KFW 40 Primary Energy Limit	kWh/m²a	21	21	21	21
Passivhaus End Energy SH Limit	kWh/m²a	15	15	15	15
Satisfy EnEV Primary Energy		yes	yes	yes	no
Satisfy KFW 40 (Optional)		yes	no	no	no
Satisfy Passivhaus (Optional)		yes	no	no	no

Initial Costs

The Initial Construction and Planning Costs are structured around Cost Groups (KG) which are used by the German construction industry [22]. The six KG's which are relevant to this study are:

- 100 : Land Acquisition
- 200 : Connection and Access
- 300 : Building
- 400 : Technical Systems
- 500 : Garden
- 700 : Planning

The German Construction Cost Index (BKI) offers reference values for construction costs for numerous object types, building components and construction styles. The BKI values are statistical averages based on a pool of historical projects and are useful to approximate KG 200-500. However, in this study they are applied in greatest detail to the KG 300-400, describing the Building and the Technical Systems.

Below are presented costs for the Land [11], as well additional site related costs such as Site Preparation [10], Connection Costs [23] and Landscaping costs [17].

Land Costs		Coop-House	Multilevel Units	Flats	Mini-Apartments
Purchase Price	€	225'000	225'000	225'000	225'000
Administrative Fees (Percent)		8%	8%	8%	8%
Administrative Fees	€	18'000	18'000	18'000	18'000
Land Total Costs (100)	**€**	**243'000**	**243'000**	**243'000**	**243'000**
Site Preparation					
Site Clearing	€/m³	15	15	15	15
Existing Volume	m³	295	295	295	295
Site Clearing	**€**	**4'400**	**4'400**	**4'400**	**4'400**
Connection Costs					
Connection per Parcel Area	€/m²	20	20	20	20
Parcel Area (GF)	m²	301	301	301	301
Total Cost (200)	**€**	**6'000**	**6'000**	**6'000**	**6'000**
Landscaping Costs					
Landscaping per Outside Area	€/m²	50	50	50	50
Outside Area (AF)	m²	217	217	217	217
Total Cost (500)	**€**	**10'800**	**10'800**	**10'800**	**10'800**

For application to the case site, reference values are taken from the following BKI reference object groups:

- Single / Double Family House Passive Massive Construction
- Single / Double Family House Passive Wood Construction
- Single / Double Family House Middle Standard
- Row End House Middle Standard

Data from these groups are adjusted in order to create reference values for objects which correspond to the Behringstrasse site, and which could be described as Row End House Passive Massive Construction or Row End House Passive Wood Construction. In addition, the factors are made specific for the city of Berlin (1.023) [17] relative to the German average and for inflation into year 2017 from 2015, the year the factors were defined (1.037) [11]. The values which are assigned from the reference objects to the Masonry and Wood constructions, are listed in the Base Component Cost Factors table (bold numbers have been assigned as they are, and underlined numbers have been averaged and assigned). The two constructions have the same cost value for example for Roof and Foundation as the constructions share the same component.

Base Component Cost Factors		Row End Passive Massive, Berlin 2017	Row End Passive Wood, Berlin 2017	Masonry Construction	Wood Construction
Pit Cost Factor per BGI	€/m^3	**38**	33	38	38
Foundation Cost Factor per GRF	€/m^2	**320**	326	320	320
Exterior Walls Cost Factor per AWF	€/m^2	**498**	**636**	498	636
Interior Walls Cost Factor per IWF	€/m^2	**202**	**241**	202	241
Ceiling Cost Factor per DEF	€/m^2	**358**	**394**	358	394
Roof Cost Factor per DAF	€/m^2	316	**354**	354	354
Int. Const. Cost Factor per BGF	€/m^2	11	46	29	29
General Cost Factor per BGF	€/m^2	**39**	**39**	39	39
Com. Cost Factor per BGF	€/m^2	12	14	13	13

Reference values are furthermore available at several levels of detail as described below:

- 1st KG Level:	Land, Building, Technical Systems, Landscape, etc.
- 2nd Element Level (Building):	Pit, Foundation, Exterior Walls, Interior Walls, Ceilings, Roof, etc.
- 3rd Component Level (Heating):	Heat Pump, Boiler, Earth Collector, etc.

Cost factors are applied at the LoD which best corresponds to the granularity of analysis of that aspect of the study. For example the costs associated with the Connection and Access (KG 200), Garden (KG 300) and Planning (KG 700) are calculated at the first LoD, while the Building and System are calculated partially at the second LoD (KG 310-330, 350-390, and 430-450) and partially at the third LoD (KG 340, 410 and 420).

Actual costs are generated by multiplying reference units of the building, taken from the Constructive Measures Table, with the cost factors. Due to the extra detail required, and to the availability of knowledge a technical systems planer, Sanitary (410) Heating System (420) positions are defined separately.

Building Cost Masonry		Coop-House	Multilevel Units	Flats	Mini-Apartments
Pit (310)	€	7'200	7'200	7'200	7'200
Foundation (320)	€	26'900	26'900	26'900	26'900
Exterior Walls (330)	€	145'800	145'800	145'800	145'800
Interior Walls (340)	€	64'700	72'200	82'800	80'400
Ceiling (350)	€	86'000	86'000	86'000	86'000
Roof (360)	€	35'700	35'700	35'700	35'700
Intgr. Constrct. (370)	€	9'700	9'700	9'700	9'700
General (390)	€	13'200	13'200	13'200	13'200
Total Building Cost (KG 300)	€	389'200	396'700	407'300	404'900
System Cost Gas Boiler					
Sanitary (410)	€	32'100	39'800	32'100	47'500
Heat (420) Base	€	31'000	30'200	25'700	26'900
Air (430)	€	12'300	12'300	12'300	12'300
High Voltage (440) Base	€	21'700	21'700	21'700	21'700
Communication (450)	€	4'400	4'400	4'400	4'400
System Total (400)	€	101'500	108'400	96'200	112'800
Total Costs (300+400)	€	490'700	505'100	503'500	517'700
Total Cost (300+400) / BGF	€/m²	1'456	1'499	1'494	1'536
Total Cost (300+400) / NUF	€/m²	2'080	2'141	2'135	2'195

A sample calculation of KG 300 and 400 costs are presented side by side in the Building Cost Table and System Cost Table for Masonry and Wood with the Gas Boiler. The Total Costs are calculated and additionally presented on a per Total Area (BGF) and per Usable Area (NUF) basis for reference and easy comparison.

Given the mostly constant exterior form of the building for all typologies, the only KG 300 reference area which varies and therefore affects the Total Building Cost is the Interior Walls Area as shown in both the Building Cost Masonry, and Building Cost Wood Tables. Whilst Total Building Costs are generally similar for all typologies of the same construction, Total Building Costs do greatly depend on the choice of construction, either Masonry or Wood.

Total Project Costs Masonry		Coop-House	Multilevel Units	Flats	Mini-Apartments
Total Land Costs (100)	€	243'000	243'000	243'000	243'000
Site Clearing and Connection (200)	€	10'400	10'400	10'400	10'400
Building (300)	€	389'200	396'700	407'300	404'900
Systems (400) (Gas Boiler)	€	101'500	108'400	96'200	112'800
Landscaping (500)	€	10'800	10'800	10'800	10'800
% Planning (700 / 300-500)		20%	20%	20%	20%
Planning 700	€	102'400	105'300	104'900	107'800
Total Construction Cost (200-700)	€	614'300	631'600	629'600	646'700
Total Initial Project Cost (100-700)	€	857'300	874'600	872'600	889'700

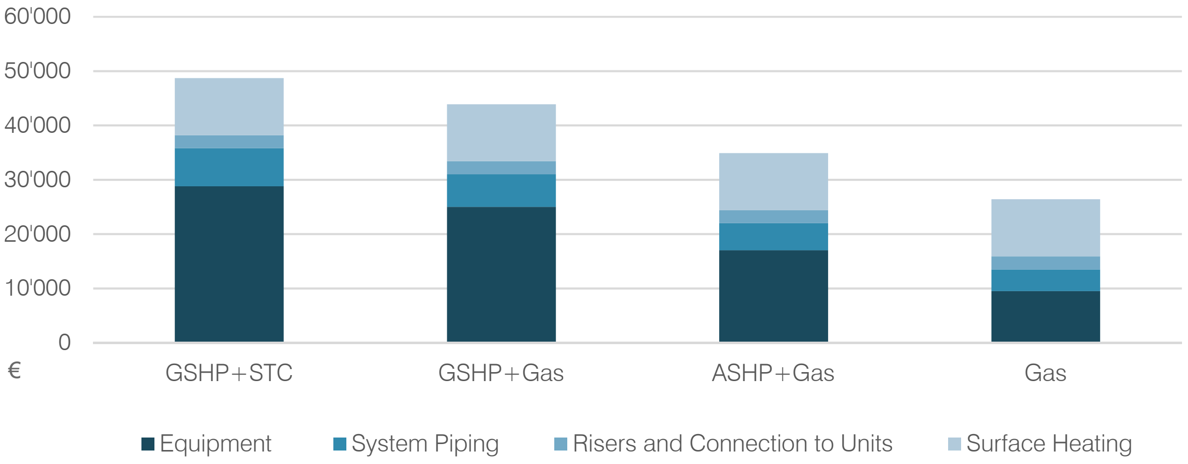
Building Cost Wood		Coop-House	Multilevel Units	Flats	Mini-Apartments
Pit (310)	€	7'200	7'200	7'200	7'200
Foundation (320)	€	26'900	26'900	26'900	26'900
Exterior Walls (330)	€	186'300	186'300	186'300	186'300
Interior Walls (340)	€	71'700	78'900	89'500	86'900
Ceiling (350)	€	94'700	94'700	94'700	94'700
Roof (360)	€	35'700	35'700	35'700	35'700
Intgr. Constrct. (370)	€	9'700	9'700	9'700	9'700
General (390)	€	13'200	13'200	13'200	13'200
Total Building Cost (300)	€	445'400	452'600	463'200	460'600
System Cost Gas Boiler					
Sanitary (410)	€	32'100	39'800	32'100	47'500
Heat (420)	€	31'000	30'200	25'700	26'900
Air (430)	€	12'300	12'300	12'300	12'300
High Voltage (440)	€	21'700	21'700	21'700	21'700
Communication (450)	€	4'400	4'400	4'400	4'400
System Total (400)	€	101'500	108'400	96'200	112'800
Total Cost (300+400)	€	546'900	561'000	559'400	573'400
Total Cost (300+400) / BGF	€/m²	1'623	1'665	1'660	1'702
Total Cost (300+400) / NUF	€/m²	2'319	2'378	2'372	2'431

Sample calculations for Total Project Costs for Masonry and Wood are also presented side by side in the Total Project Costs Tables. Planning and additional costs (700) are taken as 20% of the 200-500 costs.

The resulting costs for Wood are noticeably higher than for Masonry due to the higher costs associated with their exterior walls, interior walls and ceiling.

Total Project Costs Wood		Coop-House	Multilevel Units	Flats	Mini-Apartments
Total Land Costs (100)	€	243'000	243'000	243'000	243'000
Site Clearing and Connection (200)	€	10'400	10'400	10'400	10'400
Building (300)	€	445'400	452'600	463'200	460'600
Systems (400) (Gas Boiler)	€	101'500	108'400	96'200	112'800
Landscaping (500)	€	10'800	10'800	10'800	10'800
% Planning (700 / 300-500)		20%	20%	20%	20%
Planning 700	€	113'600	116'400	116'100	118'900
Total Construction Cost (200-700)	€	681'700	698'600	696'700	713'500
Total Initial Project Cost (100-700)	€	924'700	941'600	939'700	956'500

Heating System Costs



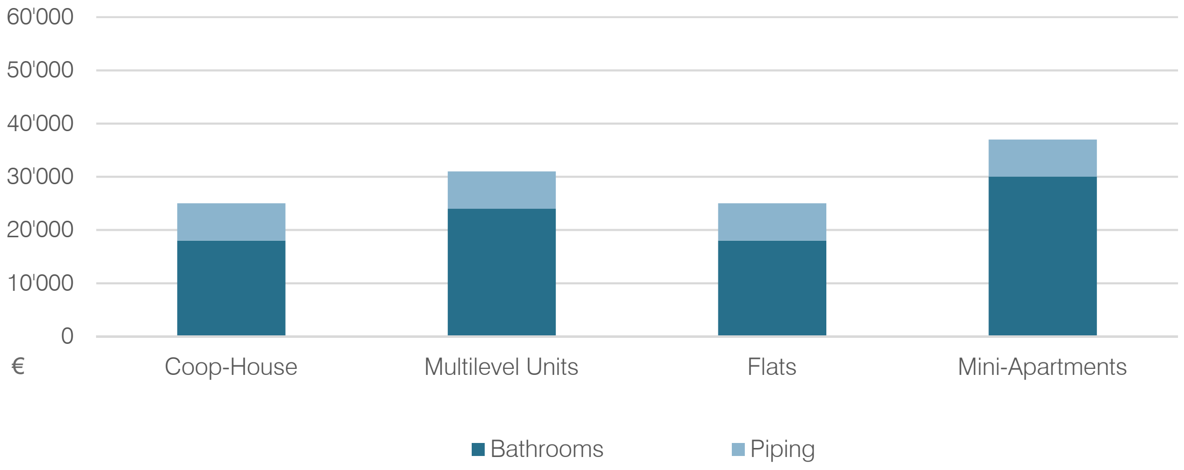
Heating Equipment Costs (Flats)		GSHP, STC	GSHP, Gas Boiler	ASHP, Gas Boiler	Gas Boiler
Heat Pump	€	8'000	6'500	6'500	-
Boiler	€	-	4'500	4'500	7'000
Solar Thermal Collector	€	8'800	-	-	-
Earth Probe	€	8'000	8'000	-	-
Hot Water Storage Tank	€	4'000	6'000	6'000	2'500
Equipment Total	**€**	**28'800**	**25'000**	**17'000**	**9'500**
System Piping	€	7'000	6'000	5'000	4'000
Risers and Connection to Units	€	2'400	2'400	2'400	2'400
Surface Heating	€	9'800	9'800	9'800	9'800
Total Heating Equipment Costs (420)	**€**	**48'000**	**43'200**	**34'200**	**25'700**

The Heating Equipment Costs as well as the Sanitary Costs were established in discussion with technical systems planer R. Ziegler [23] and verified against the BKI values. It was found that these two sources agreed well, though the structure presented by R. Ziegler, comprised of the below points, was beneficial to differentiating the system options and is applied in the study:

- Main system equipment costs (boiler, heat-pump)
- System piping, valves, and connection of the equipment
- Vertical risers and connection to above floors and units
- Surface heating

Total Heating Equipment Costs (420) depend on both typology and system. These costs range between €25’700 and €48’000 for the Flats and between €31’000 and €53’300 for the Coop-House. The main effect of typology is the amount of surface heating required, and the unit connection costs. These results show that the equipment costs for the more complex systems are relatively modest, constituting an increase of only 5% of the Total Construction Costs.

Sanitary Costs per Typology



Sanitary Costs		Coop-House	Multilevel Units	Flats	Mini-Apartments
Cost Per Bathroom	€	6'000	6'000	6'000	5'000
Quantity Bathrooms		3	4	3	6
Cost Bathrooms	€	18'000	24'000	18'000	30'000
Risers and Piping	€	7'000	7'000	7'000	7'000
Total Sanitary Costs	**€**	**25'000**	**31'000**	**25'000**	**37'000**

Sanitary Costs are composed of the following elements:

- Bathroom
- Risers and Piping

For the smaller bathrooms of the Mini-Apartments, €5’000 is allocated per bathroom, whereas €6’000 is allocated for the larger bathrooms for all other typologies.

The Coop-House and the Flats have the lowest Total Sanitary Costs of €25’000, with the Mini-Apartments reaching a total of €37’000.

Operating Revenues

The sole revenue stream generated from the project is that of the rental incomes.

A sliding scale of average rental prices per area are taken from available market data [24] and a reference object located in Behringstrasse listed on the ImmobilienScout online platform in 2016 [25]. Rents are considered without any additional costs, or as ‘cold’ rent.

Monthly and Annually Rent (Cold)		Coop-House	Multilevel Units	Flats	Mini-Apartments
Monthly Rent per Area	€/m^2	10.8	10.8	12	14.76
Rentable Area	m^2	240	243	173	170
Total Monthly Rent	€	2'594	2'624	2'076	2'510
Reference Unit		Bedroom	Unit	Unit	Unit
Monthly Rent per Ref. Unit	**€/Unit**	**519**	**1'312**	**692**	**418**
Annual Rent	**€**	31'131	31'484	24'915	30'125

Mini-Apartments are currently popular amongst developers as they can demand a relatively high rent per area. Yet due to the fact that the basement of the building does not contribute to the overall rentable area, the Mini-Apartments are not the highest earning typology.

The Flats are the least financially attractive typology from the perspective of the developer as they also have a non-rentable basement, and only an average rent price per area.

Although the Coop-House and Multilevel Units have the lowest rent per area, they both benefit from a basement with rentable area which makes them the best earning typologies.

If the developer chooses to make a greater initial investment by installing an advanced and efficient system, which also constitutes a savings in energy cost for the renter, they could attempt to argue for an increased rental price equivalent to the savings in energy costs. See subsection Operating Costs (Renter).

Operating Costs (Developer)

From the perspective of the developer, operating costs are comprised of the management cost of the property, the cost of vacancy (loss of rent), depreciation of the built object, and interest on the loan required to initiate the project.

Operating Costs		Coop-House	Multilevel Units	Flats	Mini-Apartments
Monthly Tenant Mgmt Cost	€	40	70	90	120
Monthly Building Mgmt Cost	€	90	90	90	90
Annual Mgmt Costs	€	1'560	1'920	2'160	2'520
Loss of Rent Rate		2.8%	2.8%	2.8%	2.8%
Loss of Rent (annually)	€	865	875	692	837
Cost of Future Repairs Rate		0.5%	0.5%	0.5%	0.5%
Annual Cost of Future Repairs	€	2829	2886	2880	2936
Total Project Costs	€	857'300	874'600	872'600	889'700
Ratio Base Capital		34%	34%	34%	34%
Base Capital	€	291'482	297'364	296'684	302'498
Interest Rate		1.4%	1.4%	1.4%	1.4%
Interest Due Annually	€	7'921	8'081	8'063	8'221
Total Annual Operating Costs	€	13'175	13'762	13'794	14'514

Management costs of the rental property have two components; tenant management and building management. The cost of finding and maintaining a relationship with a tenant ranges from €17 – 40 per month per unit based on guidance from German website for building management [26]. Secondly, the cost of coordinating maintenance and management of the building is set at approximately €84 for all typologies as calculated from the base case Flats in the amount of €28 per unit per month which totals approximately €1’000 annually, based on guidance from Immobilienscout [27].

The cost of vacancy is taken as 1 month’s rent over 3 years.

Depreciation exists in the form of wear on building components (e.g. energy systems, kitchen, bathroom, windows, etc.) resulting in a cost at the time the components need to be replaced. In other words depreciation is equivalent to ‘savings for future renovations and replacements’, and is taken as 0.5% annually of the total constructions costs [9].

The cost of interest is taken as the initial loan value multiplied by the interest rate. The interest rate accessible to a project developer varies greatly based on their financial profile (securities they can offer, project history, other income sources, etc.). For this project an adjusted rate is taken as 1.4% for 10 years [29].

As the costs of ongoing maintenance and small repairs to the building are passed on to the renter, they can therefore be neglected as a cost for the developer.

Operating Costs (Renter)

From the perspective of the renter, energy costs are the relevant (variable) operating costs. For the Flat typology, annual energy costs are presented in the Energy Costs Table.

Energy Price Current		GSHP, STC	GSHP, Gas Boiler	ASHP, Gas Boiler	Gas Boiler
Electricity Price Germany 2017	€/kWh	0.282	0.282	0.282	0.282
Gas Price Germany 2017	€/kWh	0.058	0.058	0.058	0.058
Energy Demand					
Electricity Fuel (SH+DHW)	kWh	3684	4928	6753	125
Gas Fuel (SH+DHW)	kWh	0	2477	135	19849
Electricity DEC	kWh	5000	5000	5000	5000
Energy Costs					
SH + DHW Costs Annually	€	1'039	1'533	1'912	1'187
SH + DHW Costs Monthly	€	87	128	159	99
DEC Costs Monthly	€	1'410	1'410	1'410	1'410
DEC Costs Monthly	€	118	118	118	118
Cost Savings					
Annual Savings	€	873	379	0	-
Monthly Savings	€	73	32	0	-

Energy costs are calculated by multiplying the current energy price with the demand. Germany pays some of the highest electricity prices in Europe at around 28.0 cents per kWh [30]. In contrast, gas is available at the comparatively low price of 5.8 cents per kWh [31]. Due to these conditions, the Gas Boiler system has an economic advantage over the other systems.

Due to the EnEV regulation a simple gas boiler based system is no longer permitted for construction, therefore this option is not a practical solution and is not included in the savings calculation. Considering the 3 remaining systems, operational cost savings can be achieved relative to the ASHP+Gas system by installing a more efficient system, either the GSHP+Gas or GSHP+STC.

Given that the more advanced systems typically require a higher initial investment, it is conceivable that the developer could seek a higher rent price through a type of warm rent deal, for an additional amount equivalent to the saving the renter would benefit from, in this analysis €380 and €870 annually respectively. In the case of the GSHP+STC this strategy would increase the annual rent by about 3%.

Energy Price Future Scenario		GSHP, STC	GSHP, Gas Boiler	ASHP, Gas Boiler	Gas Boiler
Electricity Price Future Hypothetical	€/kWh	0.250	0.250	0.250	0.250
Gas Price Future Hypothetical	€/kWh	0.085	0.085	0.085	0.085
Energy Costs					
SH + DHW Costs Annually	**€**	**921**	**1'442**	**1'700**	**1'718**
SH + DHW Costs Monthly	€	77	120	142	143
DEC Costs Monthly	**€**	**1'250**	**1'250**	**1'250**	**1'250**
DEC Costs Monthly	€	104	104	104	104

A hypothetical future scenario for the same demand is presented in the Energy Cost Future whereby electricity prices have fallen slightly to 25.0 cents and gas prices have risen to 8.5 cents per kWh. Given the trend of continued renewable energy generation buildout in Germany which has the potential to lead to reduced electricity prices, and the reality that gas is imported to Germany and subject to geopolitical conditions with the risk of price increase, this elaborated scenario is plausible.

The most noticeable impact of such a market shift would be the Gas Boiler based system losing its economic advantage and becoming one of the most expensive systems to operate.

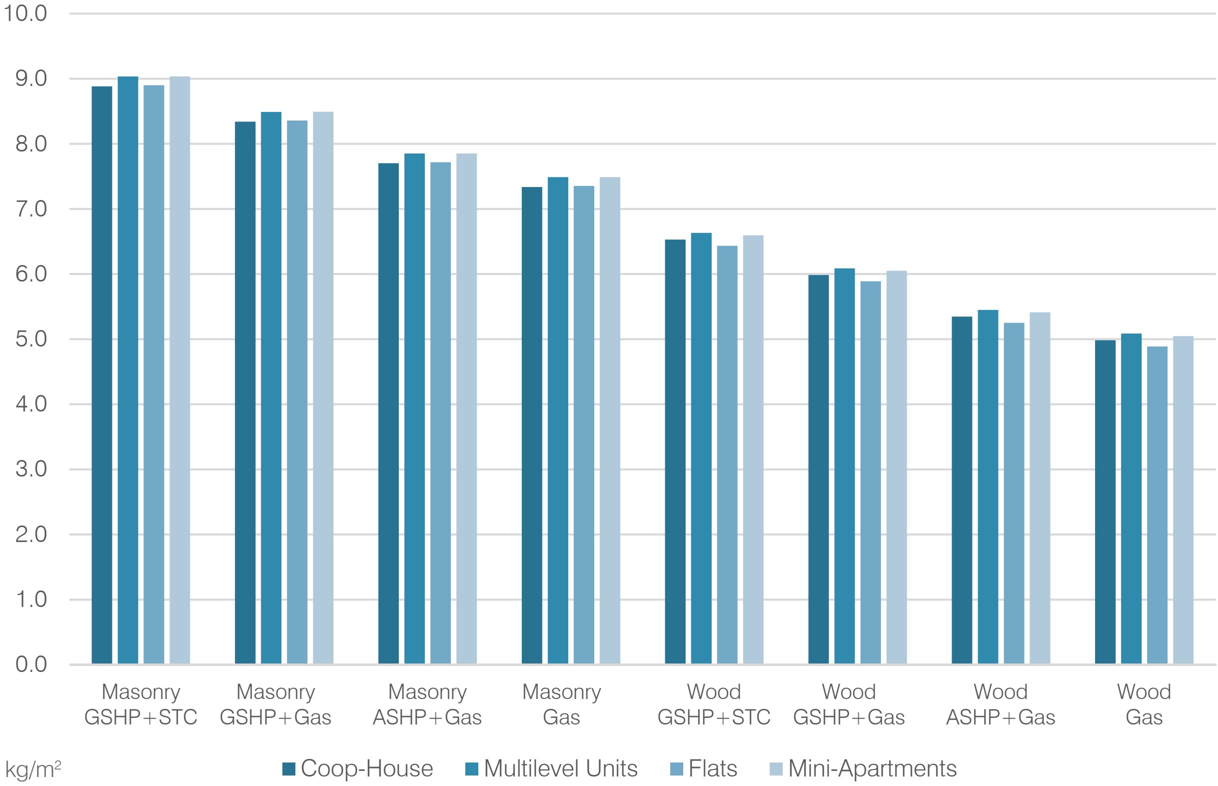
Embodied Emissions

Embodied emissions are calculated based on the material mass of all construction components according to SIA MB 2032 [8] with the help of the GREG software tool which accesses emissions data from the KBOB 2016.

As part of the assessment methodology, lifetimes in years are also assigned to each building component, which is beneficial as it does not require setting a fixed lifetime for the complete project which can be difficult to estimate. Furthermore, with this approach GREG incorporates the embodied emissions of maintenance and replacement as it assumes that the building components are automatically replaced at the end of their individual lifetimes.

All 32 permutations are assessed as the typologies, construction and systems all have an impact on embodied emissions. Results are graphed in terms of equivalent kgCO2 on a per square meter basis for a constant EBF area of 330 m2.

Embodied Emissions



The embodied emissions are influenced to a large degree by the choice of construction and system. The Masonry construction involves significantly higher embodied emissions than does the Wood. Moreover, the study shows that shifting to a system with higher operationally efficient demands a significant increase in embodied emissions.

The variation of installation density (e.g. number of bathrooms, etc.) per typology does not have a significant impact on embodied emissions.

Operating Emissions

Operating emissions are considered to be the sum of emissions associated with the production and consumption of SH, DHW and DEC.

Even though the cost of DEC is normally external to the landlord-renter relationship, it is considered for its contribution toward operating emissions in determining the overall performance of the built object.

Carbon intensity values for the European Electricity Grid ENTSO-E-Mix (Solar) 0.5256kg/kWh [32] as well as for the production and combustion of natural gas, together given 0.2025kg/kWh, are taken both from the KBOB and Carbonindependnet.org [33].

The operating emissions need only be computed for 16 permutations (4 typologies by 4 systems) provided that the operational energy for the two constructions is comparable. An example calculation of operating emissions in equivalent kgCO2 for the Flats is presented in the Carbon Emissions Table.

Carbon Intensity		GSHP, STC	GSHP, Gas Boiler	ASHP, Gas Boiler	Gas Boiler
ENTSO-E Grid Mix	kg/kWh	0.5256	0.5256	0.5256	0.5256
Natural Gas	kg/kWh	0.2025	0.2025	0.2025	0.2025
Energy Demand					
Electricity Fuel (SH+DHW)	kWh	3'684	4'928	6'753	125
Gas Fuel (SH+DHW)	kWh	0	2'477	135	19'849
Electricity DEC	kWh	5'000	5'000	5'000	5'000
Carbon Emissions					
Electricity Fuel (SH+DHW)	kg	1'937	2'590	3'549	66
Gas Fuel (SH+DHW)	kg	0	502	27	4'019
Electricity DEC	kg	2'628	2'628	2'628	2'628
Total Op. Carbon Emissions	kg	4'565	5'719	6'205	6'713
Total Op. Carbon Emis. per Area	kg/m²	14	17	19	20

An interesting point to note is that the average carbon intensity of the electric grid in Germany is higher than that of burning gas at site, due to the presence of coal fired power plants in the German generation portfolio [34].

If one could purchase an electricity mix of 50% solar and 50% gas powered generation from the grid, it would have an average carbon intensity of 0.2675 kg/kWh calculated by averaging the IPCC 2014 intensity values for these two sources [35]. This scenario would result in the operating emissions outlined in the Carbon Intensity Solar Gas Scenario Table.

Carbon Intensity Solar Gas Scenario		GSHP, STC	GSHP, Gas Boiler	ASHP, Gas Boiler	Gas Boiler
Solar Source Only Grid	kg/kWh	0.2675	0.2675	0.2675	0.2675
Natural Gas	kg/kWh	0.2025	0.2025	0.2025	0.2025
Energy Demand					
Electricity Fuel (SH+DHW)	kWh	3'684	4'928	6'753	125
Gas Fuel (SH+DHW)	kWh	0	2'477	135	19'849
Electricity DEC	kWh	5000	5000	5000	5000
Carbon Emissions Solar Gas Scenario					
Electricity Fuel (SH+DHW)	kg	986	1'318	1'806	34
Gas Fuel (SH+DHW)	kg	0	502	27	4'019
Electricity DEC	kg	1'338	1'338	1'338	1'338
Total Op. Carbon Emissions	kg	2'323	3'157	3'171	5'390
Total Op. Carbon Emis. per Area	kg/m²	7	10	10	16

By comparing the results of the two scenarios, it becomes clear that, as the average carbon intensity of the grid is reduced, the carbon performance of systems with electricity as a source of fuel will also improve.

As a basis for generating the final results, however, the carbon intensity of the current grid ENTSO-E mix is applied as the realistic value for carbon intensity of electricity consumption in Germany.

Results and Discussion

Given that all reference data and relevant sub-methods have now been introduced and developed, the final results can be generated for all 32 design alternatives according to the following relationships:

$$\text{Total Initial Project Cost (TIPC)} = \text{All Initial Costs (KG 100-700)}$$

$$\text{Total Investment (Developer)} = \text{TIPC x Capital Ratio}$$

$$\text{Net Revenue} = \text{Total Revenue – Operating Costs (Developer)}$$

$$\text{ROI} = \frac{\text{Net Revenue}}{\text{Total Investment (Developer)}}$$

$$\text{Total Annual Emissions} = \text{Embodied Emissions (annually)} + \text{Operating Emissions (SH+DHW+DEC)}$$

$$\text{Total Annual Emissions per Area} = \text{Total Annual Emissions / EBF}$$

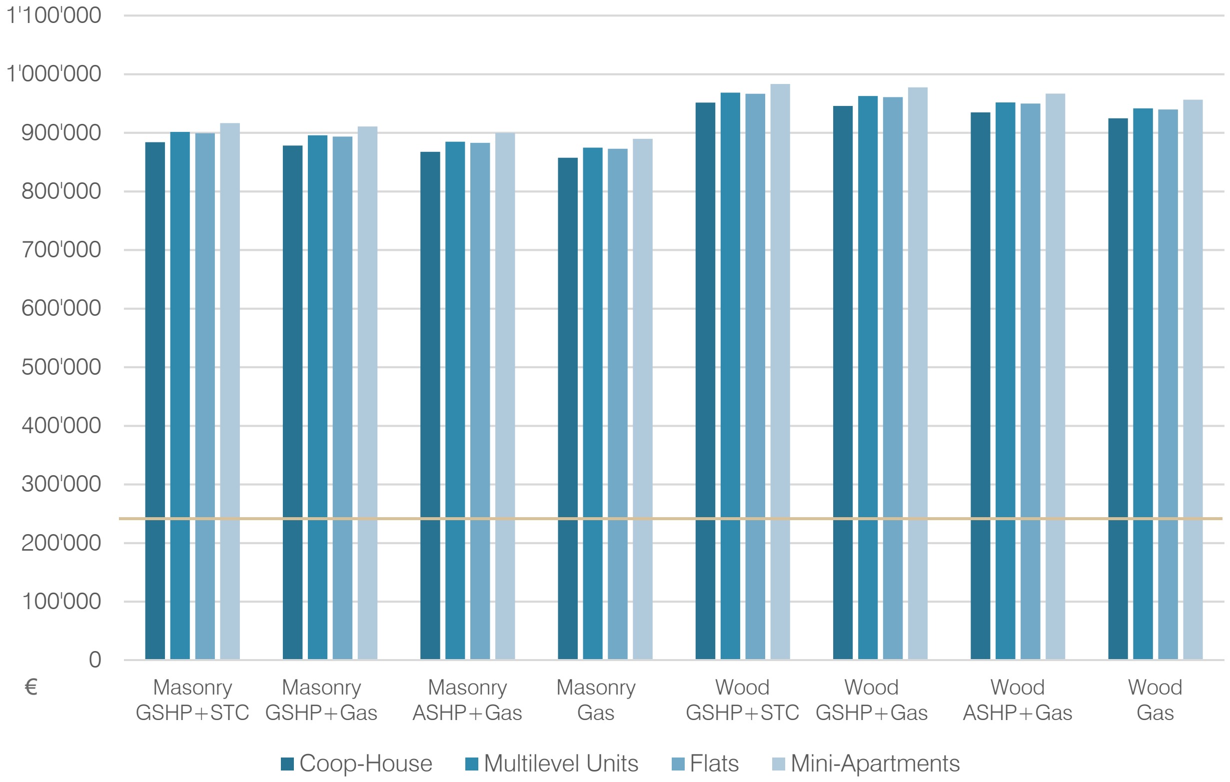
$$\text{Total Annual Emissions per Person} = \text{Total Annual Emissions / Occupancy}$$

$$\text{ROC} = \frac{\text{ROI}}{\text{Total Annual Emission per Area}}$$

$$\text{Modified ROC} = \frac{\text{Net Revenue}}{\text{Total Annual Emissions}}$$

Total Initial Project Costs

TIPC



The Total Initial Project Cost (TIPC) includes all initial costs assessed in the study (KG 100-700). This encompasses the cost of land acquisition and clearing, planning, construction and connection of the built object as well as the garden. This total amount constitutes the total investment needed to develop the project. Indicated by the beige line on the chart is the total expenditure for the land acquisition equal to €243'000, which is held constant for all alternatives. The TIPC less the cost of land acquisition is referred to as the Total Construction Costs.

Construction

By developing a Wood construction, the TIPC is increased by up to 8% or about €67'000 over the Masonry construction. For the same comparison TCC is increased by 10%.

Typology

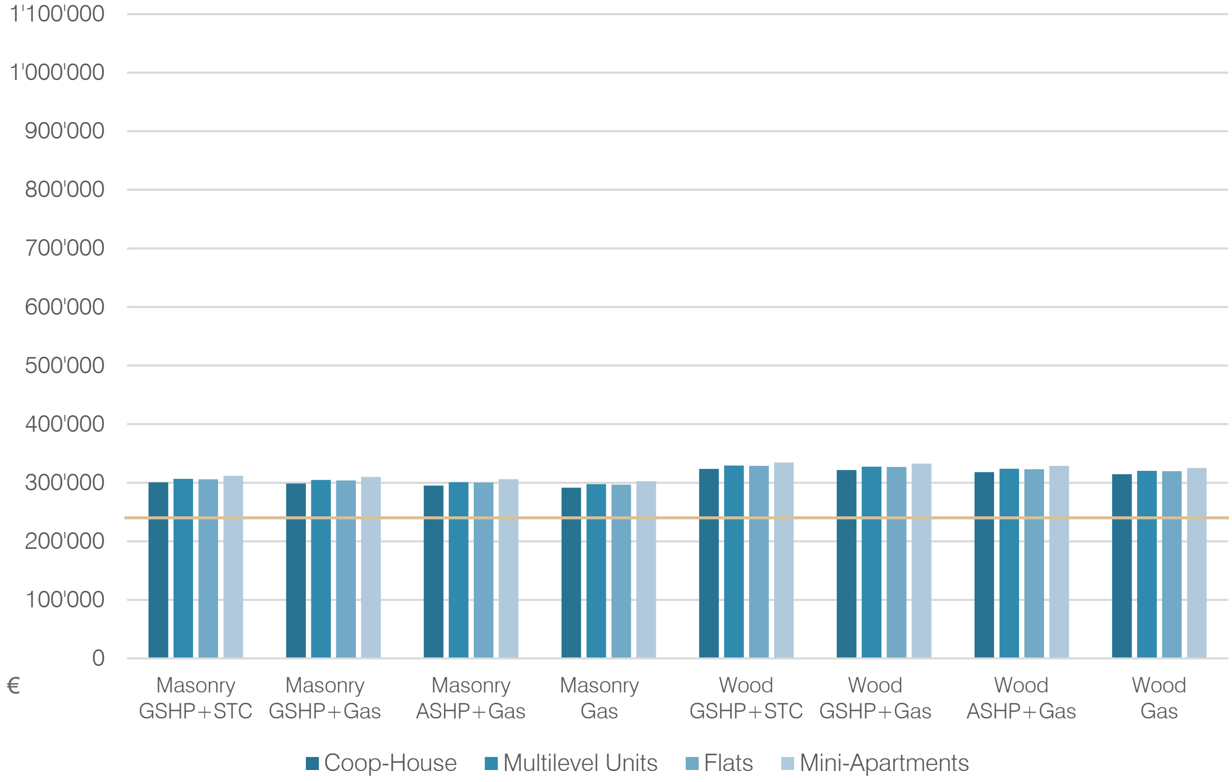
The typology varies the TIPC by 4% or €34'000, or the TCC by 5%. The Mini-Apartments are consistently the most costly option to develop.

System

By opting for the GSHP+STC System over the base case Gas Boiler System 3% or €27'000 is added to the TIPC. For the same comparison 4% is added to the TCC.

Total Investment Developer

Total Investment Developer



The total investment required of the developer is proportional to the TIPC. In this case the ratio of capital to loan is set as 34% for all alternatives. Practically speaking, this means that the developer would be able to acquire the land (cost indicated by the beige line on the chart) within their own resources, though would depend on external sources to finance the construction.

Construction

A Wood construction increases the developer's investment in the project by up to 8% or €23'000 over the Masonry construction.

Typology

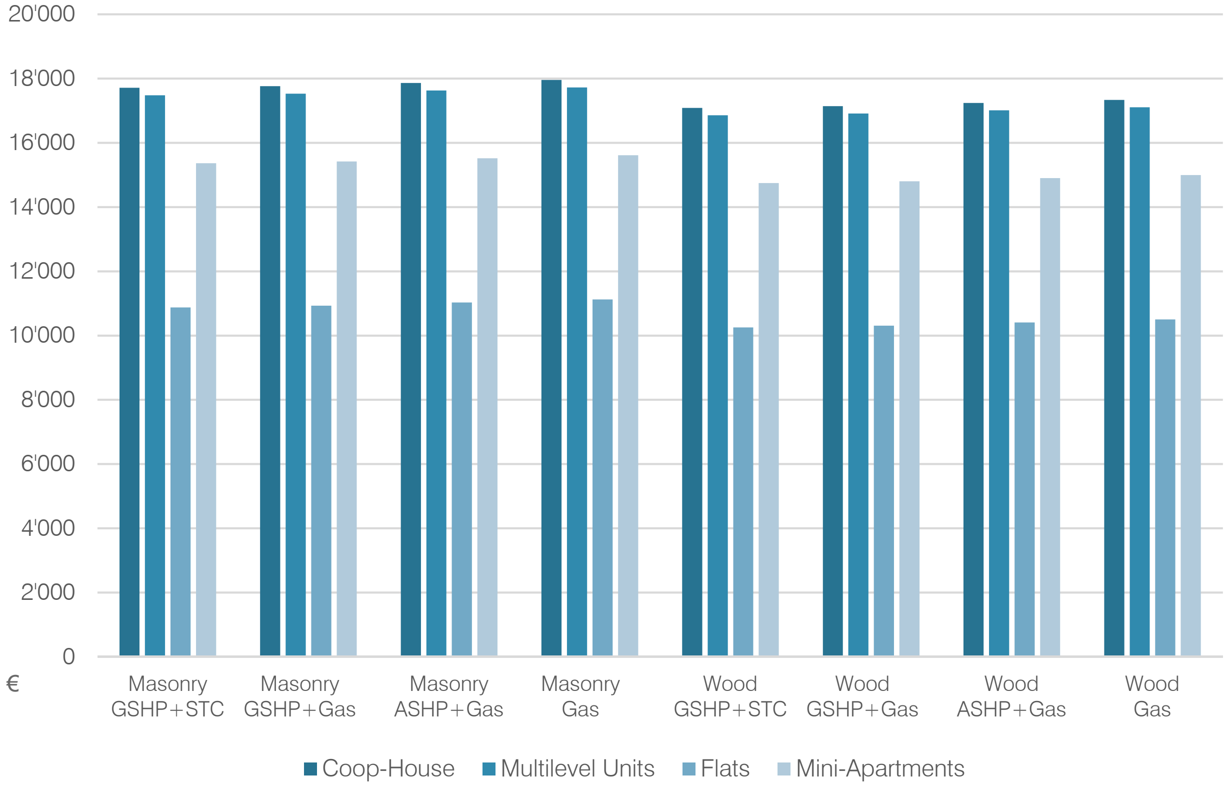
Upgrading to the GSHP+STC System over the base case Gas Boiler System adds 3% or €10'000 to the investment.

System

Choosing between typologies results in a 4% variation of the developer's investment equal to €12'000.

Net Revenue

Net Revenue



Construction

The correlation between construction type and net revenue is the amount of interest due on the loan for the project. Given that the Masonry construction costs are comparatively lower than those of Wood, this results in a lower TIPC, lower loan amount, lower interest payments and ultimately higher Net Revenue.

Typology

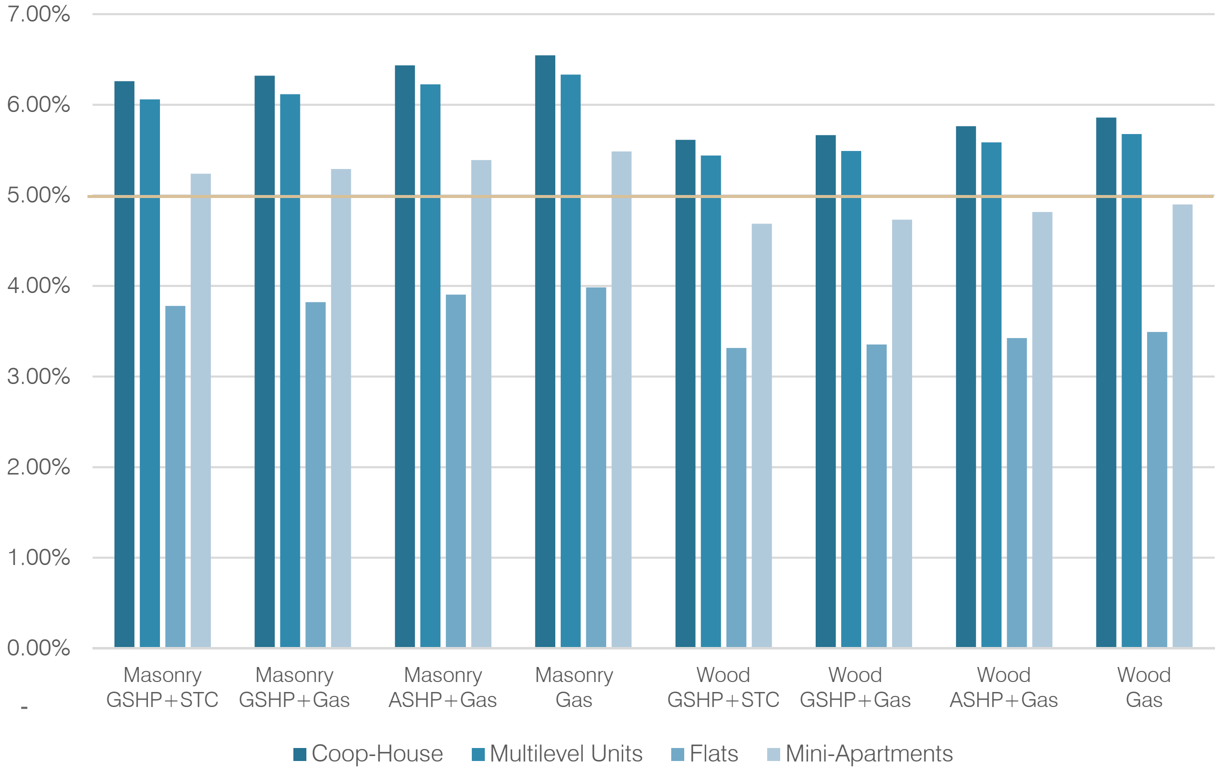
The typology has the biggest effect on net revenue. Across the board, the Flats result in the lowest level of net income due to the fact that they generate the lowest total monthly rent. Total monthly rents are calculated by multiplying the rental price per area by the rentable area. Although the Flats do not have the lowest rental price per area, when combined with their rentable area (to which the basement level does not contribute) the results are the lowest.

System

The systems have only a small effect on net revenues as they are not considered to have an effect on the total monthly rent.

Return on Investment

ROI



The beige line represents the 5% ROI marker, under which some developers and other investors may find projects to be unattractive, given the inherent risk of development.

Construction

The lower cost of Masonry construction increases the ROI noticeably by close to one percentage point for all alternatives with this construction type.

Typology

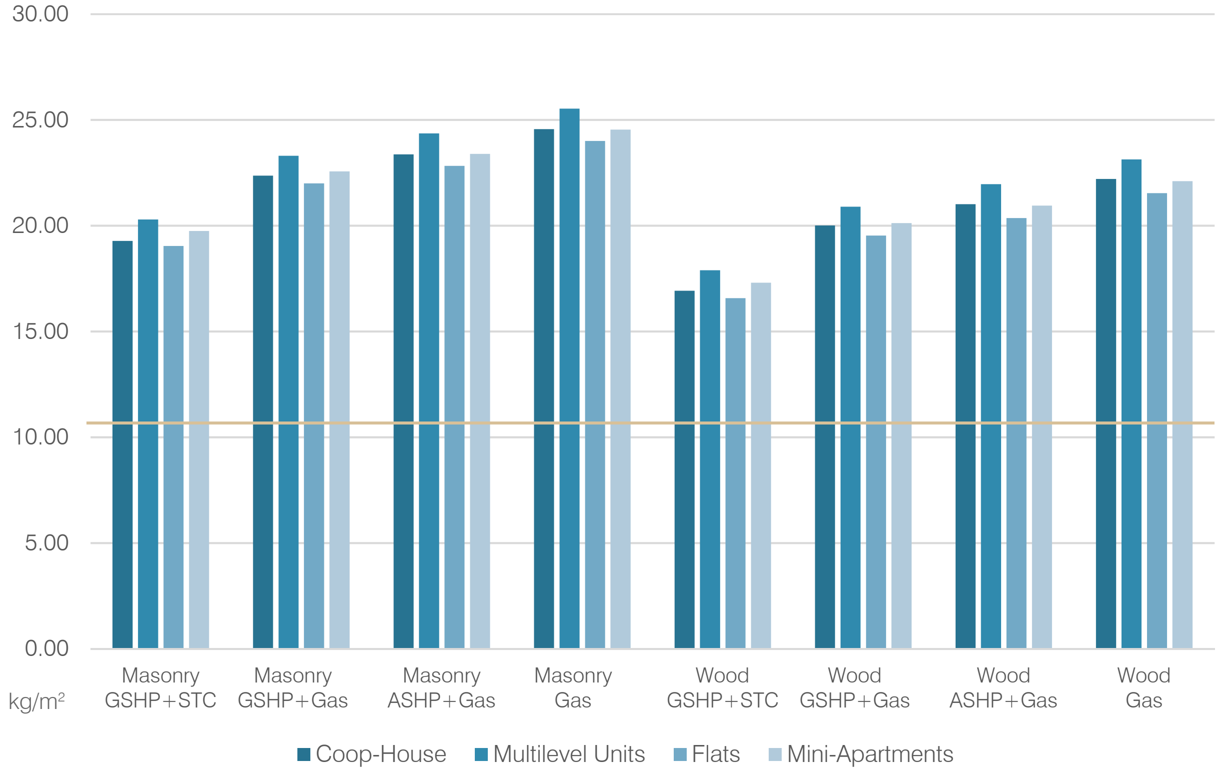
Flats have the lowest ROI in each grouping, around 4% for Masonry construction and around 3% for Wood construction. The Mini-Apartments outperform the Flats on average by about 1.5% ROI, in total laying between 6 and 7% ROI for Masonry and between 4.5 and 5.5% for Wood construction. The Coop-House and Multilevel-Units perform comparably well, above 6% for Masonry and above 5.5% for Wood.

System

The ROI drops as the systems go from the lower cost Gas Boiler system, to the higher cost GSHP+STC system, though by only 0.5% over the whole range.

Total Annual Emissions per Area

Total Annual Emissions per Area



The beige line indicates the 2000WS goal of 11 kg/m² of equivalent CO2 emissions for the combined construction and operation of a residential building annually. None of the design alternatives currently meet the 2000WS goal.

Construction

By choosing a Wood construction, about 2.5 kg/m² can be saved annually over Masonry. This is for the most part due to the difference of embodied emissions of the two materials, as wood has significantly lower embodied emissions than masonry.

Typology

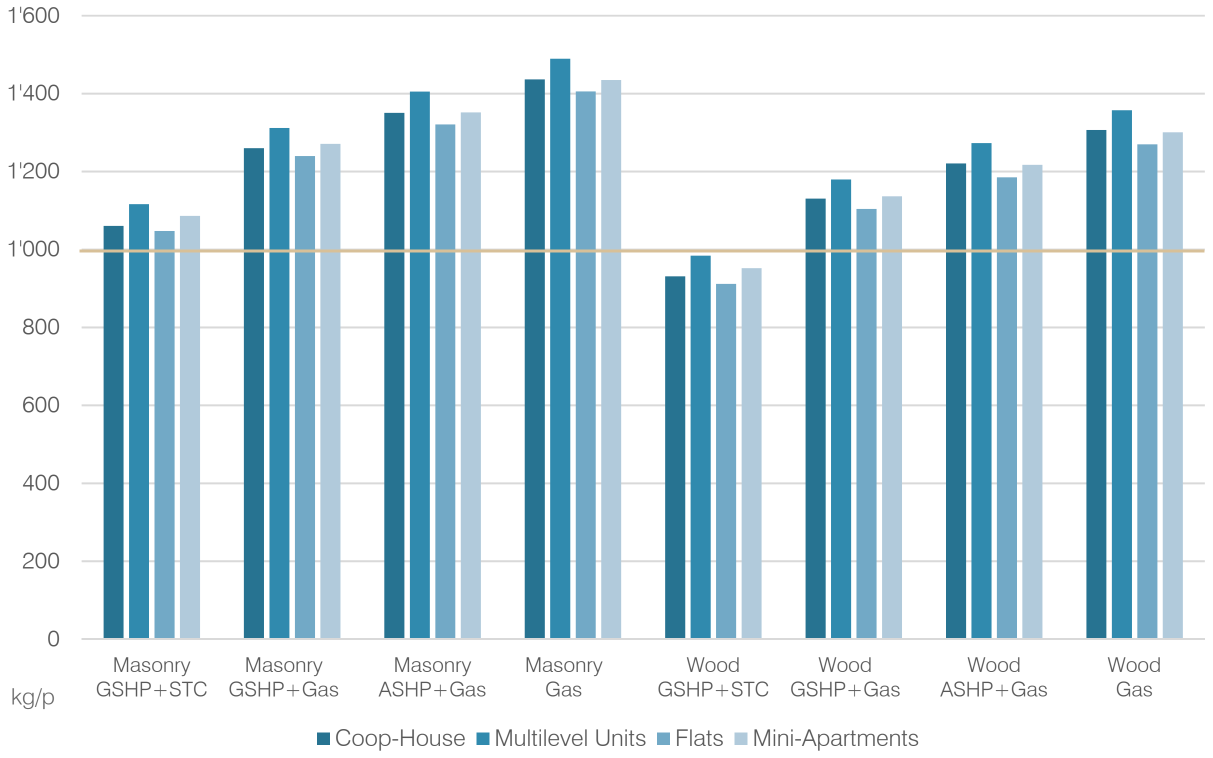
Even though the typologies have a similar installation density, and similar energy demands, they have a variation of 1.5 kg/m² annually.

System

Despite the higher embodied emissions of the more advanced systems such as the GSHP+STC, their operational carbon efficiency more than compensates for it. As a result, design alternatives with more advanced systems tend towards the lowest total annual emissions, where it is possible to save 5 kg/m² over the base case Gas Boiler.

Total Annual Emissions per Person

Total Annual Emissions per Person



Given that the occupancy for all typologies is equal to 6, the Total Annual Emissions per Person chart mimics that of the Total Annual Emissions per Area. The beige line indicates the 2000WS goal of 1’000 kg of equivalent CO2 annually per person. While the design alternatives with the combination of Wood and GSHP+STC have emissions less than this limit, the chart is misleading as the emissions considered in the study include only building construction and operation, and not other aspects of the 2000WS philosophy, such as mobility – a significant component – which would also need to be satisfied in under 1’000 kg. Therefore, it can be concluded that none of the current design alternatives meet the 1’000 kg goal of the 2000WS in a realistic way.

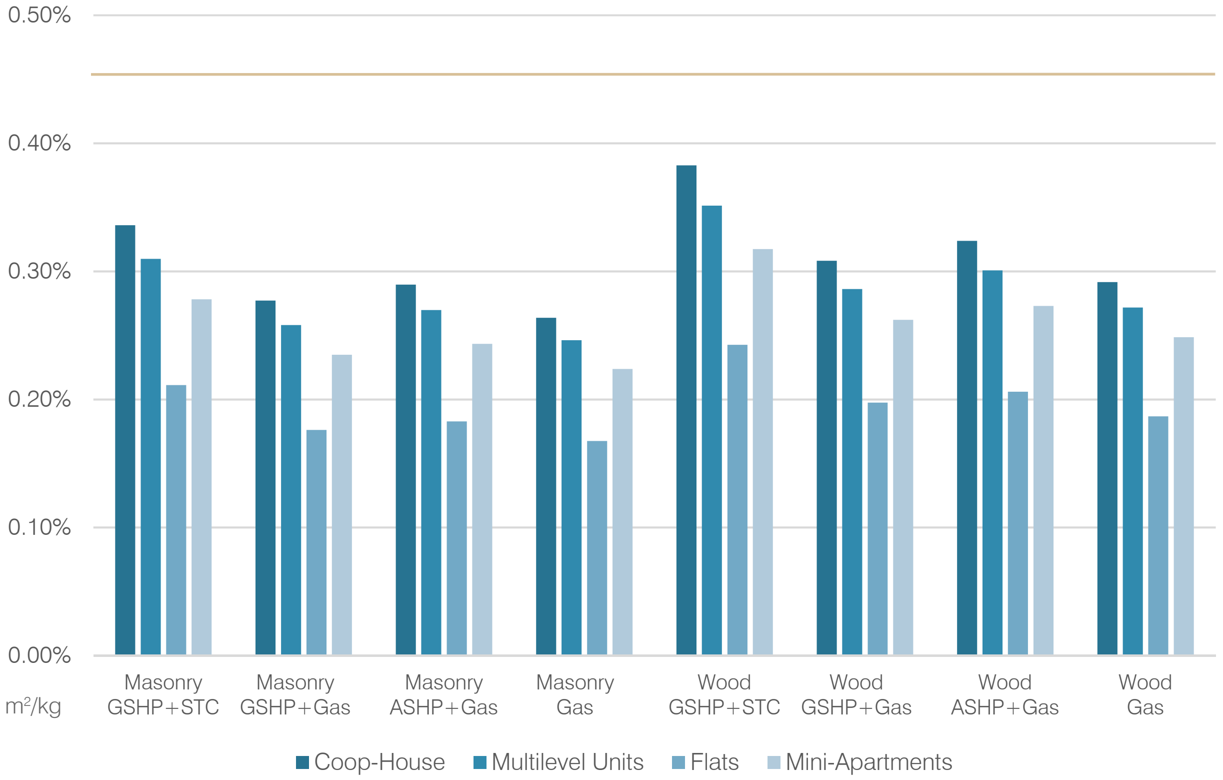
Construction
By choosing a Wood construction, about 100 kg can be saved annually per person over Masonry.

Typology
As the range of typologies have a similar installation density, and similar energy demands, they have only a minimal influence on the emissions per area.

System
By opting for an advanced system, each occupant of the building can save around 360 kg of carbon emissions each year.

Return on Carbon

ROC



As ROC is defined as the quotient of two rates, ROI and Total Annual Emissions per Area, it is not sensitive to the extent of the project. Meaning, if the projects were doubled in size, the ROC would not be affected. As a result, ROC is a term which can be applied to compare projects of various scales.

Furthermore, as ROC is a new term, it is difficult to reference the results against anything except themselves. To put this into context, the beige line is inserted at 0.46% representing the ROC of a project with an acceptable ROI of 5%, and an outstanding carbon performance of 11 kg/m^2 as per the 2000WS.

Construction

Contrary to the findings for ROI, the Wood construction is on average 14% more attractive than Masonry in terms of ROC. Based on this switch, it can be said that the financial gain of constructing with the less costly Masonry system comes at proportionally higher carbon cost.

Typology

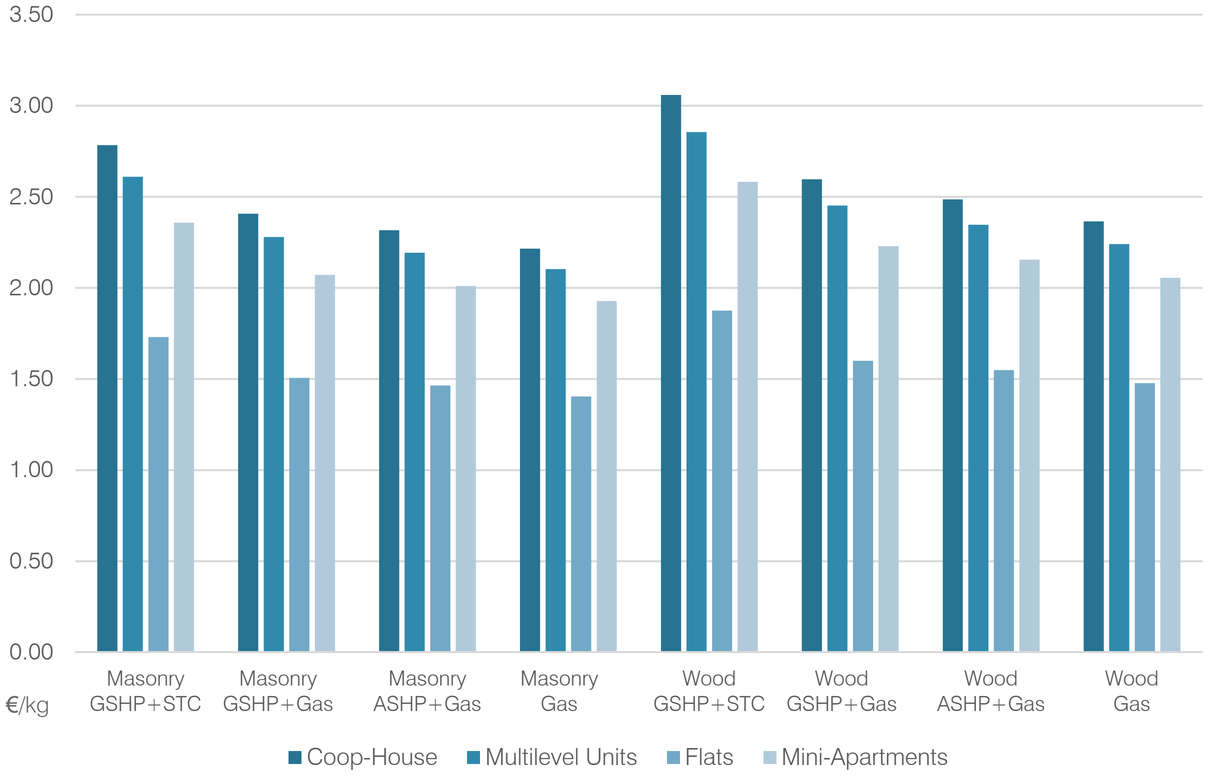
While the pattern of ROC values across typology are similar to ROI, the Coop-House more clearly stands out as the best performing typology in terms of ROC, due to its high ROI and relatively low carbon emissions.

System

The trend line of ROC across systems slopes opposite to ROI. GSHP+STC has the highest ROC, while ASHP+Gas shows a local peak between the Gas and GSHP+Gas Systems.

Modified Return on Carbon

Modified ROC



The Modified ROC is the relative measure of Net Revenue per Total Annual Emissions. Even though Net Revenue and Total Annual Emissions are both extensive values, and therefore individually sensitive to the scale of the project, their quotient is an intensive value which can be compared between projects, and potentially even outside of the real-estate industry. Moreover, the resulting values of the Modified ROC, and their units (Euro / kg) are more easily comprehensible, representing the carbon cost of earning money. Overall the Modified ROC trend is similar to ROC.

Construction

Like with ROC, the Wood construction shows better results over Masonry, though by around 10%.

Typology

Across groupings the Coop-House continues to show strong performance, with the Multilevel-Units and Mini-Apartments slightly lower. The Flats show the lowest Modified ROC values.

System

The Modified ROC trend follows that of ROC, though ASHP+Gas does not exhibit a local peak.

Conclusion

Insights into Design Alternatives

The building envelopes created by the two constructions – Masonry and Wood – achieved similar overall performance in terms of combined transmission and ventilation losses. This means that the superior insulating quality of wood was degraded by its typically less airtight construction, compared to masonry.

Even though one typology may appear to have a much higher installation density than another, for example the Mini-Apartments versus the Coop-House (as one has 6 and the other only 3 bathrooms in total), the variation in TIPC between them is 4% and would likely not be the basis for selecting a typology. Variation in the net revenues of the typologies is however quite large, up to 40%, and would strongly influence the choice of typology to develop in practice.

The Coop-House and Multilevel Apartments show similarly strong results in terms of ROI, though according to ROC and Modified ROC the Coop-House is the most favourable candidate for development.

Despite the relatively low emissions of the Flats, they are nonetheless the least attractive typology for the Behringstrasse site in terms of Net Revenue, ROI, and ROC.

The cost increase of upgrading from the base case Gas Boiler system to the GSHP+STC system constitutes an increase of only 3% of TIPC. This cost increase alone would likely not disqualify any of the more advanced systems, therefore even the GSHP+STC can be considered as a realistic option for development in practice.

The Wood construction has superior carbon performance over Masonry, saving up to 30% of the emissions associated with the construction.

The operational carbon emissions savings of advanced energy systems over their lifetime more than outweigh the additional embodied energy required for their construction. The systems offer a bigger lever over the constructions and typologies to influence/reduce carbon emissions (either in total, on a per area or a per person basis).

The price difference of energy delivered from the electricity grid versus the gas grid is significant, whereby the cost of gas is currently less than one quarter that of electricity on a per energy unit basis. This combined with the fact that the burning of gas is less CO2 intensive than the current German electricity grid average, makes gas an attractive fossil fuel. Therefore hybrid systems which are fueled in part by gas at the site can benefit from this advantage.

Though as the price of gas gradually rises, the operating costs of the systems will shift and the relative economic performance of the advanced and more carbon efficient systems will improve. In this case, advanced systems will become favourable to the renter of the building, which could allow the developer to recoup some of the additional construction costs through a warm rent deal.

Additional Design Strategies

Design Typologies accommodating Increased Occupancy
Thanks to the layout of the Coop-House and Multilevel-Units, their occupancy could both easily be pushed up from the 6 occupants considered in this study to 7. Although increasing occupancy does not affect the inherent performance of the building on a per square meter basis, it will reduce the emissions on a per person basis, therefore helping the building occupants to reduce their personal emissions, potentially to under 1’000 kg annually.

Ensure the Source and Carbon Intensity of Electricity from the Grid
It was shown that the average CO2 intensity of the German electricity grid is high due to the presence of coal fired power production within the energy mix. Therefore, if one buys electricity produced from a mix of solar and gas, this would be significantly better than the grid average, and would improve the overall carbon performance of the building and its users.

Comments on the Methodology

Design Alternatives
By defining the design alternatives as a typology, construction and system, the study not only responds to technical and economic questions of development, but allows as well to respond to social questions concerning the viability of various living forms.

Refining of the Simulation
The simulation of the building envelope and system produced certain results which would demand further investigation in order to increase confidence in them.

The building envelope performance resulting from the Design Builder simulation, was found to have a noticeable dependence on airtightness. As a result, the difference in airtightness of the Wood and Masonry (0.65 and 0.70 ACH respectively) cancelled the difference in the quality of their thermal insulation. Furthermore, while it is relatively straightforward to define the insulating quality of a building simply based on its materials, it is not possible to establish the airtightness of a building simply based on its construction as defined in this study.

The Polysun generated performance results of the ASHP+Gas system showed an unexpected proportion of gas to electricity consumption. In order to verify this result the system model would need to be further debugged or reconstructed in a slightly different configuration to generate a new set of values for comparison.

Simplification of Method
There are some ways in which to accelerate the application of the method, in order to arrive at an ROC result faster. One such possibility would be, to simplify the method by moving away from the Design Builder simulation software and in its place, make use of reference values and a hand calculation to assess the energy balance and demand of the building.

Return on Carbon
ROC and Modified ROC have both offered additional insight into the design alternatives beyond the previously existing methods such as ROI.

ROC has been defined as an expression of relative economic to per square meter carbon performance, though its resulting units are convoluted (m^2/kg) and not ideal. Modified ROC may have the potential to be a more useful measure, as its units (€/kg) are more tangible, and moreover its results understandable as the relative carbon cost of earning money.

On the other hand, due to being both relative measures, an associated risk with ROC and Modified ROC is that they have the potential to make alternatives with high economic performance and low carbon performance, look comparable to alternatives with high carbon performance and low economic performance.

Further Study

Return on Carbon
It would be interesting to conduct an analysis of Modified ROC for other real-estate projects or potentially for a large real-estate portfolio company in order to generate results for comparison and to develop further insights into the term.

Behringstrasse Site
PV was not included in the current study at the building level due to the slope of the roof being ill suited for solar collection. However, there would be the potential to evaluate the construction of a South-West facing PV wall at the rear of the garden at the Behringstrasse site. On the one hand this installation would benefit from easier installation at the ideal angle of about 45°, and on the other, it could serve as a noise barrier between the rails and the building. Such a system would also have the potential of being extended to the neighbouring land parcels on the same street. Though the performance of the system would first need to be assessed, specifically taking into consideration the shadowing caused by the building.

Locally produced electricity from PV could be offered to the residents of the street at a favourable rate which would also improve the overall carbon performance of the building.

In general, PV generated electricity has one of the lowest CO2 intensities of any source, and will continue to need to be developed extensively in order to approach the various energy and carbon efficiency goals discussed in this study.

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